Estuaries and Coasts

# Salt marsh accretion and storm tide variation: An example from a barrier island in the North Sea

--Manuscript Draft--

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| **Abstract:** | We reconstruct past accretion rates of a salt marsh on the island of Sylt, Germany, using measurements of the radioisotopes 210Pb and 137Cs, as well as historical aerial photographs. Results from three cores indicate accretion rates varying between 1 and 16 mm yr-1. Comparisons with tide gauge data show that high accretion rates during the 1980's and 1990's coincide with periods of increased storm activity. We identify a critical inundation height of 18 cm below which the strength of a storm seems to positively influence salt marsh accretion rates, and above which the frequency of storms becomes the major factor. Beyond the impact of sea level rise, we conclude that for high inundation heights occurring in lower marsh zones, the mean strength of storms is predominantly affecting marsh accretion, while for low inundation heights, occurring in higher marsh zones, the frequency of storms is the dominant driver for marsh accretion. |

**COVER LETTER - SUBMISSION OF REVISED MANUSCRIPT**

Kiel, October 27, 2011

Subject: **SUBMISSION OF REVISED MANUSCRIPT:**

"*Salt marsh accretion and storm tide variation: An example from a barrier island in the North Sea"*

Dear Editor(s),

I would like to thank you for the evaluation of the revised manuscript (first submitted on the 11th of January 2011). We have addressed all the minor modifications suggested by the 2 reviewers and have revised the manuscript accordingly.

Based on the suggestions of reviewer #1, we revised figure 1 and all other figures by increasing their resolution and incorporating the other suggested modifications. Furthermore, we converted the bulk density numbers to SI-units and double-checked all the numbers throughout the manuscript. We are confident that all numbers are now correct.

Addressing the comments of reviewer #2, we rewrote the abstract, including the methods of how we constructed the presented geochronology and focusing on historical responses of salt marsh accretion rates in relation to storm pattern rather than future predictions. We also made some corrections within the manuscript removing speculative parts about future developments. Concerning the estimation of autocompaction, we included a rationale for only using the upper 5 cm of the cores for analysis within the "Methods" section.

The additional modifications suggested by the reviewers have further improved the manuscript and we are confident that the paper is now ready for publication.

Please find enclosed the revised manuscript, together with the detailed answers to the comments of the 2 reviewers.

Sincererly yours

Mark Schürch

Reply to reviewer #1

Please note: Replies in violet are the most recent replies to the 2nd review of reviewer #1.

**Comments from review #1**

Study site
Line 81. Are these coordinates right? As far as I can tell from Google Earth, this is a site in west Jutland in Denmark??
Coordinates were corrected to 54°54'N, 008°20'E.

*Please state the coordinates for sampling site. You need to be more precise. Now we are on Sild, but in the middle of a town. Include the seconds as well.*

Coordinates were changed to 54°47'18''N / 008°17'30''E. This corresponds to a location in the middle of the investigated salt marsh.

Figure 1. This is a poor figure. The top figure seems to be out of proportions.
The coordinate system of the top figure was changed from WGS 1984 to ETRS 1989 UTM, this will hopefully help the reader understand the figure.

*This is still a poor figure. The resolution seems to be too low (at least in my copy). In the bottom right figure I can't find neither the Path/Road nor the Veg. not specified. Either delete these two legends or find a way to make them clear on the figure.*

We increased the resolution of figure 1 and all other figures to 300 dpi. We deleted the "Road / Path" entry from the legend and made the "Vegetation not specified" more visible in the figure.

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***New comments for review #2***

*S 12 RESULTS*
*Please use SI units and state the dry bulk density in kg $m^{-3}$*
We changed the units of bulk density from kg $dm^{-3}$ to kg $m^{-3}$. We also changed the respective numbers in figure 3.

*S 12 line 289. I think there is a typo here, the dry bulk density cannot be 9.39 kg $dm^{-3}$ (pure solid quartz is around 2.6 kg $dm^{-3}$).*
The value was corrected to 939 kg $m^{-3}$.

*S 12 Line 299. The same, the DBD is too high at 5-6 kg $dm^{-3}$*
The values were corrected to 500-600 kg $m^{-3}$.

*S 12 line 293. The same (3.25 & 6.56 kg $dm^{-3}$)*
The values were corrected to 325 and 656 kg $m^{-3}$.

*S 13 line 294. The same (4.5-5 kg $dm^{-3}$)*
The values were corrected to 450-500 kg $m^{-3}$.

*S 13 line 304-308. I think you mean decrease instead of increase in the upper 5 cm. Is the decrease significant?*
Since all other bulk density values are reported from a top-down perspective, we would rather use the same method here. This means that it is an increase with depth.
The increase can be represented by a logarithmic regression at a significance level of $p<0.02$. The paragraph was reworded respectively: "*The increase of bulk density within the uppermost 5 cm of core S1 was found to fit the logarithmic model (equation 6; $R^2=0.97$, $p<0.02$), which is considered as evidence for autocompaction. Model parameters A and B were estimated to be 0.0879 and 0.3791, respectively. The autocompaction rate during the growth of the salt marsh therefore averages 1 mm yr-1.*"

*As far as I can tell from fig 3, all densities are below 2 kg $dm^{-3}$, and most of the fine grained material is around 0.5 kg $dm^{-3}$.*
In fact, most fine grained material is around 500 kg $m^{-3}$ in cores S2 and S3. However this is different in S1, where bulk density increases with depth from about 325 to 656 kg $m^{-3}$. This should also be detectable in figure 3.

*S 16 line 370. The acc rate of 1.5 – 1.8 mm / yr does not correspond with the numbers in Table 1 (1 – 1.2 mm/yr)*
The numbers in the text were changed to 1-1.2 kg $m^{-3}$.

*IN GENEREL, THE AUTHORS SHOULD DOBBLE CHECK ALL NUMBERS IN THE MANUSCRIPT.*
All numbers were double checked: Besides a few minor changes, we have corrected the value for the mean accretion rate in S3 from 4 mm $yr^{-1}$ to 2.5 mm $yr^{-1}$ and the threshold for the inundation depth from 26 cm to 18 cm.
We are sure that ALL number are correct now.

*S 19 line 444. Don't you mean S1 and S2. As far as I can tell S3 does not contain Cs137.*
We do mean core S2 and S3. The fact that S3 does not show a 137Cs peak supports the dating since this suggests that the marsh started to develop after 1986. A respective explanation was added: *"The absence of a peak in core S3 also supports what we can observe in the aerial photographs, as well as the $^{210}$Pb dating suggesting that the marsh development started after 1988."*

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*Figures: you seem to have exchanged fig 5 and fig 6.*
Revised as suggested.

*Fig 12: you need a label on the x-axis*
We added the following label for the x-axis: *"Storm water level (m above NN)"*.

Replies to reviewer #2

Reviewer #2: I have read the article by Schuerch et al., in which they use sedimentary geochronologies to examine how marshes in the Wadden Sea have responded to climate variability over the past century, and how the might respond to future changes in climate over the next century. Overall, this is a pretty good paper. However, I think it needs one substantial change and several more minor ones before it can be accepted for final publication.

Thank you for reviewing the paper and for your very valuable feedback. We revised our paper according to your suggestions and are happy to see that the paper has considerably gained from these changes.

**Major changes:**
The most important changes that are needed are with respect to the authors' analysis of how these marshes will respond to future changes in climate. In their abstract, they write, "Future development of low-lying marsh zones will therefore be controlled by mean high water levels, while upper marsh accretion rates will be controlled by storm activity. We suggest that climate change has a higher impact on the marsh zonation rather than on marsh survival." This statement is too broad.

This sentence was worded: *"Beyond the impact of sea level rise, we conclude that for high inundation heights occurring in lower marsh zones, the mean strength of storms is predominantly affecting marsh accretion, while for low inundation heights, occurring in higher marsh zones, the frequency of storms is the dominant driver for marsh accretion."*

In this paper the authors have mostly measured processes that occur along the vertical axis, and have not really considered what can happen along the horizontal plane. (Aside from a brief examination of aerial photographs). In other words, most of their data is core data, and not a detailed analysis of spatial change, such as might be done with a GIS. The authors don't seem to consider whether increased storm activity could increase shoreface erosion, and how a decreasing marsh width might impact interior regions of the marsh. This problem needs to be corrected.

We are aware of the fact that less consideration has been given to lateral marsh development within our study. In order to emphasize this limitation we added the following phrases at the beginning of the "Influence of storm on accretion" ("Discussion"): *"The analysis presented in this study focuses on the historical vertical development of a single salt marsh. It is shown that an increase in storminess positively correlates with marsh accretion rates. While many authors have focused on the destructive, erosional influence of storms on salt marshes (e.g. Callaghan et al. 2010, Mariotti and Fagherazzi 2010, van de Koppel et al. 2005), our methods are not able to reproduce the lateral marsh development and their implications on accretion processes, but rather the vertical marsh accretion."*

I would suggest that the authors
1) focus more on their analysis of the past response of marshes to storms and sea level change, which is very well done, rather than speculate on future changes, which is more tenuous.

We removed the paragraph "Future marsh development". As you mention, it is indeed not sufficiently supported by the available data. Consequently we also reworded the respective paragraph in the "Conclusions" focusing more on what we could observe rather than what we expect for the future.

2) recognize the difference between things that are measured in a core and things that occur in the lateral environment.

The concept of the critical inundation height found in our data has spatial implications, since inundation depth is higher in the low marsh zone than in the high marsh zone. We reworded the respective phrase in the abstract (as described above) to make clear that this is the only spatial implication that we are suggesting.

**Minor changes:**
Abstract: The abstract needs a bit of rewording. The authors should avoid the passive voice whenever possible. Also, the authors could include a few more specifics- such as by noting how the geochronologies were constructed.

The abstract was reworded. We replaced the formulations with passive voice and added the three methods employed for the reconstruction of historic marsh accretion.

Lines 35-36. The Kirwan citations are not right citations. It would be better to cite Redfield (1972) or Orson (1985).

Revised as suggested.

Line 54. The authors have a comma after the K+G paper, but I think they mean to have a period.

The comma follows the introductory clause “While …” and separates it from the main clause. We think that the comma is grammatically correct.

Line 79 - an elsewhere. The authors refer to figures using lowercase letters. I would prefer to see the word figure capitalized and abbreviated- as "Fig. 1." However, I will defer to the editorial staff for on any final determination of the article's style.

Revised as suggested.

Line 126. The authors should prove, or provide data, indicating that compaction was negligible.

The following sentence, summarizing the data that underlies this statement is added: *“Compaction during core collection was measured in situ as the difference between the measures from the top of the PVC-tube to the salt marsh surface outside and inside the core. This difference was found vary between 2 and 4 % of the core length (in all three cores) and was therefore assumed to be negligible.”*

Lines 170-172. Why was autocompaction only investigated in the top 5 cm. Certainly it can happen anywhere in the core. This seems weird and either needs to be explained in more detail or the analysis should be conducted on the entire core. Even if Bartholdy (2010) present a method to use this, the rationale for using their method must be explained in sufficient detail in the paper for that rationale to stand alone.

We added an explanation why we employed the method following the mentioned sentence: *“[…], since variability of bulk density triggered by changes of grain size and organic carbon content in the lower parts of the core was too large to derive reliable estimates for autocompaction.”*

Line 214. De Groot is not the right citation. This was understood long before 2009. You might try Compton (1923) instead.

Revised as suggested.

Line 280. I believe this sentence should read, "Fine grained sediments are?."

Revised as suggested.

Line 284- 308. The authors need to be more careful about the number of significant figures attached to the bulk density values. Are 4 significant figures really appropriate.

All bulk density estimates were rounded to no decimal figures (applying the SI unit kg $m^{-3}$).

Also, I am not used to seeing bulk densities listed as kg/dm3, and instead would prefer to see them as g/cm3 or kg/m3 unless the authors have a compelling reason to do otherwise.

The unit of bulk density was changed to kg/$m^3$.

Line 326 (and elsewhere). For excess 210Pb I am used to seeing the subscript XS rather than exc, and I would prefer to see that used - unless the authors have a compelling reason to do otherwise.

Revised as suggested.

Line 516. General comment: I very much like the authors analysis of storm influence on marsh accretion. It would be interesting to hear some discussion as to whether the authors think this is due to the positive shift in the NAO as some (e.g. Hurrell et al., 2001) or whether this is an imprint of an acceleration in global sea level rise rates as others (e.g. Kolker et al., 2010), have noted.

We are aware of the close relationship between storminess and the NAO index suggested by some authors, but we could not find this relationship in our data. We think that a positive shift in the NAO index could positively influence salt marsh accretion. However our data does not prove this hypothesis sufficiently to discuss it within the paper. We currently conduct further investigations on separating the different climatic influences on salt marsh accretion by means of modeling.

Line 588. The authors write, " No confident predictions for the future development of storm patterns are available at the moment." This sentence is a bit poorly constructed and should be rewritten.

As stated earlier this paragraph was removed altogether.

Figure 8. The horizontal lines in this figure are kind of ugly. I think that this happens when you make figures in MS excel. There is a way to get rid of these lines, and this should be done.

Revised as suggested (all figures were compiled in Matlab).

# Salt marsh accretion and storm tide variation: An example from a barrier island in the North Sea

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## ABSTRACT

We reconstruct past accretion rates of a salt marsh on the island of Sylt, Germany, using measurements of the radioisotopes $^{210}$Pb and $^{137}$Cs, as well as historical aerial photographs. Results from three cores indicate accretion rates varying between 1 and 16 mm yr$^{-1}$. Comparisons with tide gauge data show that high accretion rates during the 1980's and 1990's coincide with periods of increased storm activity. We identify a critical inundation height of 18 cm below which the strength of a storm seems to positively influence salt marsh accretion rates, and above which the frequency of storms becomes the major factor. Beyond the impact of sea level rise, we conclude that for high inundation heights occurring in lower marsh zones, the mean strength of storms is predominantly affecting marsh accretion, while for low inundation heights, occurring in higher marsh zones, the frequency of storms is the dominant driver for marsh accretion.

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## KEYWORDS

*Salt marsh, accretion rate, geochronology, storm activity, barrier island, Sylt*

# INTRODUCTION

Coastal salt marshes in the Wadden Sea (southeastern North Sea) are abundant leeward of the East Frisian and North Frisian barrier islands as well as in front of the dike system on the Dutch-German-Danish North Sea coast. Salt marshes serve as coastal protection structures by reducing the impact of waves on the upper shoreline (e.g. Möller, 2006) and as important habitats for specialized plants and animals including migratory and breeding waterfowl, and breeding birds (Reise et al., 2010). The existence of salt marshes is critically dependent on how fast sediment accretes relative to sea level rise (Orson et al., 1985; Redfield, 1972). Salt marshes are complex coastal features, governed by various physical and biological processes creating a system that exists in dynamic equilibrium with relative sea level rise (RSLR; Allen, 2000). Salt marsh accretion, defined as the vertical growth of the marsh, occurs when organic and/or inorganic sediments are deposited onto the marsh during inundation (allochthonous growth), as well as when salt marsh plants grow and decompose (autochthonous growth; Dijkema, 1987; Kolker et al., 2009). Projected acceleration in SLR, however, may outpace accretion rates in the future, if an insufficient amount of material is deposited on the marsh surface (Kirwan and Temmerman, 2009; Orson et al., 1985). Several investigators studied marsh response to mean sea level rise (French, 1993; Kirwan and Temmerman, 2009; e.g. Orson et al., 1985; Reed, 1995), others investigated the influence of tidal range on salt marsh accretion (e.g. Chmura et al., 2001; Harrison and Bloom, 1977; Kirwan and Guntenspergen, 2010), but relatively little literature is available discussing the impact of non-tidal short-term sea level variations on salt marsh accretion (Bartholdy et al., 2004; French, 2006; Kolker et al., 2009; Temmerman et al., 2003b). While it is a widespread assumption that

53 macrotidal environments are more resilient against SLR than microtidal
54 environments (Kirwan and Guntenspergen, 2010), Allen (2000) and Kolker et al.
55 (2009) conclude that marsh accretion is dominated by wind-induced (short-term)
56 sea level variations in microtidal, and by SLR-induced long-term sea level
57 variations in macrotidal environments. It remains unclear how wind-induced sea
58 level variations enhance the resilience of the salt marsh, and in particular, whether
59 many minor storms are more effective in triggering accretion than a few major
60 storms. This is noteworthy as certain studies suggest that the storm activity in the
61 German Bight has increased in recent years and will most likely increase in the
62 near future leading to more frequent storm surges and/or higher storm surge water
63 levels (Beniston et al., 2007; Fischer-Bruns et al., 2005; Rockel and Woth, 2007;
64 von Storch and Weisse, 2008; Woth et al., 2006).
65 The goal of this work is to reconstruct the development of a back-barrier salt
66 marsh on the island of Sylt, Germany, by using both $^{210}$Pb and $^{137}$Cs as
67 geochronometers. $^{210}$Pb and $^{137}$Cs are often used for studying soil and sediment
68 processes (Armentano and Woodwell, 1975; Delaune et al., 1978; Goodbred and
69 Kuehl, 1998; He and Walling, 1996b; Kolker et al., 2009). These data will be
70 combined with information gathered from aerial photographs. We report how the
71 marsh has been growing during the last decades and compare accretion rates with
72 historical tide gauge data in order to infer how storm activity affects marsh
73 accretion and its resilience against accelerated SLR.

74 **Study site**

75 The island of Sylt is located in the German Wadden Sea (54°47’18’’N,
76 008°17’30’’E), in the south-eastern North Sea (Fig. 1). Its core is made of
77 Pleistocene protruding outcrops. About 7000 years B.P., during a period of SLR

78 deceleration (Milne et al., 2005), local sea level reached its current position and
79 sandy spits were formed north and south of the original Pleistocene outcrop
80 (Ahrendt and Thiede, 2001). Sylt is an elongated barrier island with a total area of
81 99 km² extending 40 km from north to south and ranging from 1 to 13 km in
82 width (Kelletat, 1992). The western coastline is characterized by extensive
83 beaches and dunes, and, due to a relatively steep offshore elevation gradient, it is
84 exposed to highly energetic wave activity from the North Sea (Ahrendt and
85 Köster, 1998). The sheltered eastern coastline is fringed by extensive tidal flats.
86 Salt marshes are found in the transition zone from dunes to tidal flats and have a
87 total area of approximately 5 km² (TMAP - The Trilateral Monitoring and
88 Assessment Program 2006).
89 The mean tidal range, as of 2010, at the nearby tide gauge *Hörnum Hafen* is
90 2.06 m (WSA - Wasser- und Schifffahrtsamt Tönning, 2007), varying from 1.8 m
91 at neap tide to 2.3 m at spring tide (BSH - Bundesamt für Seeschifffahrt und
92 Hydrographie, 2008). Tidal range has constantly increased in the Wadden Sea,
93 including the *Hörnumtief,* since 1955 (Jensen and Mudersbach, 2004).
94 The immediate study area is located in the southern third of Sylt between the
95 villages of Rantum and Hörnum, and is characterized by the typical morphology
96 of a barrier island. A transect from the open North Sea to the tidal flats is marked
97 by a sequence of beaches, dunes, and salt marshes (Hildebrandt et al., 1993).
98 These dunes developed a dense grass and scrub vegetation and became stable, as a
99 consequence of intense planting activities since 1864 (ALW - Amt für Land- und
100 Wasserwirtschaft Husum, 1997). The area of the investigated marsh is about
101 0.3 $km^2$, with a length of about 2 km and a width ranging from 80 m to 280 m.
102 The salt marsh itself has a typical zonation ranging from pioneer marsh vegetation
103 at the seaward edge to high marsh vegetation close to the foot of the dunes (Fig.

1). The pioneer marsh is dominated by the introduced cordgrass *Spartina anglica*, the low marsh zone is dominated by *Atriplex portulacoides*, and the high marsh zone by *Juncus gerardi* and *Elymus athericus*. The vegetation is not grazed by domestic livestock.

The elevation of the salt marsh ranges from about 0.7 to 1.5 m above NN (NN: German reference datum; Fig. 2), while the mean high water level (MHW) is at about 1 m (NN; WSA - Wasser- und Schifffahrtsamt Tönning, 2007). The topography of the marsh is rather homogeneous, with a small marsh cliff (10-20 cm height) at the transition from pioneer to low marsh (Fig. 2). It is therefore assumed possible to reconstruct the historic evolution of this salt marsh by analyzing one transect only.

# METHODS AND ANALYSIS

## Sample collection and preparation

Three marsh cores were collected on 22 January 2009 using PVC tubes with an inner diameter of 11.8 cm. Cores were collected on a shore-normal transect, within the three dominant vegetation zones (Fig. 1, 2) and had a length of about 50-70 cm. S3, the most seaward core, was collected about 30 m from the seaward edge of the pioneer marsh, while S2 and S1 were located about 60 m and 110 m inland from the seaward edge respectively (Fig. 2). The large diameter of the tube was chosen in order to reduce possible compaction of the soil during collection, as well as to amass a large volume of material for accurate analysis. Compaction during core collection was measured in situ as the difference between the measures from the top of the PVC-tube to the salt marsh surface outside and

inside the core. This difference was found to vary between 2 and 4 % of the core length (in all three cores) and was therefore assumed to be negligible.

The transect where the cores were taken was leveled by hand using a dumpy level on a tripod. The height of the (seaward) starting point was determined by comparison of measured flooding and HW times between the starting point and the tide gauge in *Hörnum Hafen.* Elevations of the 3 core locations, as of today, are 0.94 m (S3), 1.34 m (S2) and 1.44 m (S1) above NN (Fig. 2). S3 is the only core location that is regularly inundated, while S1 and S2 are only inundated during storm tides.

After extraction, the cores were sliced into layers with a thickness of 1-5 cm. The thickness of the layers progressively increased towards the bottom of the core. The sediment was freeze-dried and ground manually in order to disintegrate the conglomerates of sediment. The ground material was filled into Petri dishes with a diameter of 52 mm and embedded into epoxy resin, which prevented $^{222}$Rn from degassing. The dry weight of the aliquots embedded for radiometric analysis ranged from 17.25 to 43.44 g. Samples were allowed to sit for at least 3 weeks in order to reach equilibrium between $^{226}$Ra and $^{214}$Bi before analysis.

## Sedimentology: Grain size, organic carbon content, and bulk density

Salt marsh sediment was analyzed for grain size, organic carbon content, and bulk density in order to derive the depths of the base layer and for calculation of radioisotope inventories. Grain size measurements were conducted using laser diffractometry (Malvren Mastersizer 2000). Although this method is supposed to measure grain sizes ranging from 0.02 to 2000 µm (Malvern Instruments Ldt, 2010), gradually increasing uncertainties in the coarser spectrum of grain sizes were observed during pre-measurements. Therefore, the sediment was sieved at

1000 µm before the measurements. The preparation of the samples included the destruction of organic carbon, using $H_2O_2$, and iron if necessary, using sodium bicarbonate, sodium citrate, and sodium dithionite. The measurements were conducted at obscuration rates between 5 and 30 %.

The organic carbon content was measured using the element analyzer Euro EA, which performs C/N analysis. The organic carbon is oxydized in the system and escapes as $CO_2$ into a gas chromatographer where total C (and N) content is determined.

The bulk density (ρ) was indirectly calculated from the organic carbon and the water content ($O_C$ and W) in the samples as not enough sample material was available in the upper layers for direct measurement. Assuming a constant density for water ($\rho_W$=1.02 g cm$^{-3}$) and for mineral and organic matter ($\rho_M$=2.6 g cm$^{-3}$, $\rho_O$=1.2 g cm$^{-3}$ respectively), the bulk density was calculated using the following formula (Kolker et al., 2009):

$$\rho = \frac{1-W}{\frac{W}{\rho_W} + \frac{1-W}{(1-O_C * \rho_M) + (O_C * \rho_O)}} \qquad (5)$$

Additional measurements on dry bulk density and relative water content were conducted on cores extracted on the 18 May 2011 in order to validate these bulk density calculations. It was shown that the results of the model fit the measured data ($R^2$=0.98, p<0.01).

## Assessment of autocompaction

Bulk density calculations were used for the assessment of autocompaction within the cores S1, S2, and S3. Bulk densities within the uppermost 5 cm of the salt marsh cores were investigated for autocompaction (Bartholdy et al., 2010), since

variability of bulk density triggered by changes of grain size and organic carbon content in the lower parts of the core was too large to derive reliable estimates for autocompaction. A logarithmic curve (equation 6) was fitted through the calculated bulk density data (BDD) within the uppermost 5 cm.

$$BDD = A * \ln(z) + B \qquad (6)$$

where A and B are constants to be optimized and z is the depth of the respective salt marsh layer.

If the model was found to significantly represent the bulk density data ($p<0.05$), autocompaction was included into the calculation of accretion rates by decompacting the core. Decompaction was performed by calculating the thickness of a layer in depth z ($T_z$) to the time when it was deposited using the inverse version of the equation presented by Williams et al. (2003):

$$T_z = \frac{BDD_z}{BDD_0} * T_0 \qquad (7)$$

where $BDD_0$ and $T_0$ are the bulk dry density and the thickness of today's surface layer, respectively.

## Radiometric measurements

$^{137}Cs$ ($t_{1/2}$ =30.2 years) is a product of nuclear fission, and is highly particle reactive (He and Walling, 1996b). In Europe, it is marked by two main periods of atmospheric fallout (1963 and 1986) producing two useful marker horizons (Delaune et al., 1978; Kirchner and Ehlers, 1998; Pedersen et al., 2007). The $^{137}Cs$ peak around 1963 is produced by a series of tests of nuclear bombs during the 1950's and 1960's, while the 1986-peak is a result of the nuclear disaster in Chernobyl. Some authors have found an additional $^{137}Cs$ signal in cores taken along the North and the Baltic Sea, peaking between 1974 and 1977 (Andersen et

al., 2000; Kunzendorf et al., 1998). However given the low initial activity and the 30 year half-life of $^{137}Cs$, these activities are probably below detection limits today. $^{210}Pb$ ($t_{1/2}$ =22.3 years), on the other hand, is constantly being supplied from the atmosphere via the decay of its grandparent nuclide $^{222}Rn$ (Koide et al., 1972; Walling et al., 2003). This continuous deposition makes $^{210}Pb$ an excellent geochronometer for deriving accretion rates in coastal salt marshes (Appleby and Oldfield, 1978; Appleby and Oldfield, 1983; Bartholdy et al., 2004; Bellucci et al., 2007; Kirchner and Ehlers, 1998).

A low-background coaxial Ge(Li)detector was employed to measure total gamma-ray activity of $^{210}Pb$, $^{226}Ra$, and $^{137}Cs$. It is a non-destructive counting method that allows simultaneous measurement of all three radionuclides (Nikulina, 2008). Measurement of $^{226}Ra$ is necessary, because it is a proxy for supported $^{210}Pb$. The analysis was conducted by the 'Laboratory for Radioisotopes' in Goettingen, Germany. $^{210}Pb$ was measured via its gamma peak at 46.6 keV, $^{137}Cs$ via its peak at 661.7 keV, and $^{226}Ra$ via the peaks of its granddaughters $^{214}Pb$ and $^{214}Bi$ at 352 keV and 609.3 keV/1120.3 keV respectively. The measurement time for all samples was 250,000 seconds.

## Errors / Detection limit

Errors generally increase towards the low energy gamma ray spectrum, since the background radiation is elevated as a consequence of the Compton effect of higher energetic radionuclides (Compton, 1923). Meanwhile for higher energy spectra, the background radiation decreases continuously. For $^{210}Pb$ that is measured at 46.6 keV (very low energy) this is of particular importance, since the background radiation within the sample may be elevated above the $^{210}Pb$ activity of the soil sample, resulting in measurements below detection limit.

Another source of error for radiometric measurements is the background radiation of the environment, which is quantified by measuring a parallel blank sample and minimized by increasing the sample volume as well as the counting time.
The combined "internal" and environmental background radiation at 46.6 keV is therefore higher than the activity measured for $^{226}$Ra in higher energy spectra and detection limits can be included into the analysis as maximum values for $^{210}$Pb activities.

## Dating model

The constant rate of supply model (CRS) is employed for the dating of sediment characterized by variations of initial concentrations (Appleby and Oldfield, 1978; Appleby and Oldfield, 1983). It is therefore useful in study sites with irregular inundation, where accretion rates strongly vary with time. This model allows for the calculation of the age of the sediment by using radioisotope inventories (Appleby and Oldfield, 1978; Kolker et al., 2009).
Due to the relative elevation of the core locations within the tidal frame (Fig. 2), irregular inundation occurs during storm surges, negating the assumption that accretion rates are constant over time. Therefore the CRS model was used for this study.

## Aerial photographs

Aerial photographs of the investigated area, provided by the *Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz Schleswig-Holstein (LKN-SH)*, were utilized in order to analyze the historic extension of the salt marsh during the last century and to verify the radiometric measurements. Photographs were available from 1937, 1958, 1988, 1999, 2003, and 2007. After georeferencing the

pictures and overlaying the core locations, visual interpretation was performed in order to classify the core location into the categories ‘marsh’ and ‘no marsh’.

## Hydrological data

Annual data about mean sea level (MSL) were calculated from annual mean high water (MHW) and mean low water (MLW) levels (Hofstede 2010: pers. comm.). Storm frequency and storm intensity were aggregated from the high water levels, collected for every tidal cycle between 1938 and 2007 (Wahl 2010: pers. comm., Wahl et al. 2011). Eustatic sea level rise was included into the analysis as an underlying trend that was removed from the original dataset before storm parameterization was conducted. Global SLR data, presented by Church and White (2011), were used for that purpose due to a lack of reliable estimates of local eustatic SLR.

Storm activity was parameterized by storm frequency, defined as the number of tides above a certain storm level, and by storm intensity, defined as the mean height of these storm tides. For storm parameterization, we used these definitions in order to ensure that storm intensity is statistically independent from storm frequency. Mean sea level in turn was calculated as a function of MHW and MLW (Wahl et al., 2010).

Mean values of storm intensity and frequency data were aggregated for all years in which an estimate for accretion rate was available, using a moving average filter. Taking into account an expected error and temporal resolution of the dating of the sediment layers, the window size was chosen to be 5 years.

### Analysis of storm-related salt marsh accretion

One of the main objectives of this study is to investigate the influence of storm frequency and storm intensity on the observed accretion rates. Multiple linear regression analysis was employed to assess how much of the variation within the accretion rate time series can be explained by one of these parameters. This analysis was carried out by including all high water levels that flooded the marsh from 1938-2007. By gradually increasing the storm level, and therefore excluding the low inundation events, we investigated how different high water levels were influencing accretion rates in the past. The standardized coefficients (ß) of the multiple linear regressions, as well as the p-values were compared for the different storm levels.

# RESULTS

### Grain size analysis and organic carbon content, and bulk density

In each of the cores a fine-grained upper layer is underlain by layers comprised of mainly coarse-grained sediments. The transition zone in core S1 is very distinct and fine-grained sediments are not present below a depth of about 10 cm (Fig. 3). In contrast, the transition zones in cores S2 and S3 are more gradual. Fine-grained sediment is, in fact, present throughout the entire core S2 (Fig. 3).

Bulk densities reproduce this pattern of fine-grained sediments on top of a coarse-grained base layer by increasing at the interfaces of salt marsh sediments and the sandy base layer (Fig. 3). In core S1, a clear increase of bulk density is observed at a depth of about 10 cm, reaching 1574 kg $m^{-3}$. The high bulk density of 1469kg $m^{-3}$ at the depth of 4.5 cm is considered as an outlier and was therefore excluded from the analysis. Instead, the average from the neighboring upper and

lower layers was employed. The increase in S2 is more gradual and constant, with a maximum bulk density of 939kg $dm^{-3}$ at 27 cm. In core S3, a considerable increase in bulk density is observed at a depth of about 5 cm, with a maximum value of 1591 kg $m^{-3}$. Within the silty salt marsh sediments bulk densities in cores S2 and S3 do not significantly increase, mostly varying between 500 and 600 kg $m^{-3}$. In core S1 a significant increase from 326 to 656 kg $m^{-3}$ within the uppermost 6 cm is observed, bulk density then decreases to 450-500 kg $m^{-3}$ in the lower silty layers.

Salt marsh sediments are characterized by fine-grained material with high organic content, which allows for visual and experimental determination of the thickness of the marsh layer deposited on top of the sandy base. Herein, the base of the marsh can clearly be identified in cores S1 and S3 at 8.5 cm and 4.5 cm respectively; whereas it is not as clear in core S2 (Fig. 3). The fine-grained fraction rapidly decreases at 21 cm, but increases at 23 and 27 cm again. Although high fractions of sand at depths of 21 and 25 cm are found, marsh development seems to have started at a depth of about 27 cm.

The increase of bulk density within the uppermost 5 cm of core S1 was found to fit the logarithmic model (equation 6; $R^2=0.97$, $p<0.02$), which is considered as evidence for autocompaction. Model parameters A and B were estimated to be 0.0879 and 0.3791, respectively. The autocompaction rate during the growth of the salt marsh therefore averages 1 mm $yr^{-1}$.

## Aerial photographs

The first photograph available, taken in 1937 (Fig. 4a), provides strong evidence for the presence of marsh at locations S1 and S2, however no marsh is yet present at location S3. A sand bar seems to have formed between the seaward edge of the

marsh and the adjacent tidal flat. At the landward edge of the marsh sand appears to be transported onto the marsh surface. However, in the following photograph from 1958 (Fig. 4b), sand transport onto the marsh at the landward edge seems to be less visible than in 1937; meanwhile the sand bar at the seaward edge has developed further offshore. Recent photographs from 1988 and 1995 (Fig. 4c+d) do not show considerable changes of the marsh extension towards the land, but do indicate a seaward expansion. In 1988 (Fig. 4c), core location S3 is found to be in a channel between the developing pioneer marsh and the mature main part of the marsh. The photo from 1995 (Fig. 4d), shows that the channel appears to be closed and covered by pioneer marsh vegetation. Marsh development at core location S3 is, therefore, estimated to have started between 1988 and 1995.

## Radioisotope data

### *$^{210}$Pb data*

All three depth profiles of excess $^{210}$Pb ($^{210}Pb_{XS}$) generally decrease as expected (Fig. 5). Large variations are found in the surface concentrations, with the highest activity (232 Bq kg$^{-1}$ in 1.5 cm) in core S1. Distinct peaks are found at a depth of 1.5 cm in all three cores.

In core S1 a slow decrease is observed, due to relatively high activities (116 Bq kg$^{-1}$, 112 Bq kg$^{-1}$) at depths of 4.5 and 5.5 cm. Activities below 10 cm are all less than the the detection limit and therefore less than 12.6 Bq kg$^{-1}$ (Fig. 5). The initial decrease in S2 is much greater, and influenced by low activity at 4.5 cm (below detection limit of 9.5 Bq kg$^{-1}$). Activities below 4.5 cm decrease slower, eventually resulting in activities below the detection limit for all depths lower than 17 cm (Fig. 5). In core S3, $^{210}Pb_{XS}$ also quickly decreases within the

upper 7 cm from 129 Bq $kg^{-1}$ at 1.5 cm to less than 2.6 Bq $kg^{-1}$ at 7.5 cm. $^{210}Pb_{XS}$ activities at lower depths are all below the detection limit (Fig. 5).

As $^{210}Pb$ activities in the sandy substrate of the cores S1 and S3 are all below the detection limit, normalization for grain size and organic carbon content of these activities is impossible. In core S2, where the fraction of fine grained, highly organic sediment is rather constant within salt marsh layers, normalization is not necessary.

### *$^{137}Cs$ data*

$^{137}Cs$ peaks are found in cores S1 and S2. In core S3, no $^{137}Cs$ peak was found. S1 is characterized by a major peak at a depth of 5.5 cm (267 Bq $kg^{-1}$) and a minor peak at 8.5 cm (38 Bq $kg^{-1}$; Fig. 6). $^{137}Cs$ appears to decrease towards zero at about 15 cm, although it should be considered that the sediment below 10 cm is very coarse and the effect of coarse grained sediment might reduce the $^{137}Cs$-activity (He and Walling, 1996a). In core S2 the situation is clearer: 2 peaks are found in depths of 5.5 cm (64 Bq $kg^{-1}$) and 17 cm (52 Bq $kg^{-1}$); we note that the upper peak's activity is significantly lower than the activity in S1 (Fig. 6). The $^{137}Cs$ activity in core S3 is missing a distinct peak and has a very low activity (<1 Bq $kg^{-1}$) in the sandy base layer. Finer sediments in the upper layers are marked by a slight increase in activity up to 8 Bq $kg^{-1}$ (Fig. 6).

### *Age of base layer*

The age of the marsh and the mean accretion rates were determined by radioisotope dating ($^{210}Pb$) and compared with aerial photographs (table 1). The base layer at core location S1 is found at a depth of about 8.5 cm (Fig. 2, 3). Aerial photographs show that the marsh was present in 1937. However, analysis

of $^{210}$Pb data does not support this finding, suggesting the marsh to be younger. Several $^{210}$Pb data in core S1 and S3 are below the detection limit due to a relatively high baseline activity in these samples. Since the detection limit is considered as a maximum activity and allows for activities within the range of zero to the detection limit, the original error range needs to be extended. Therefore the year when the base layer was deposited (according to $^{210}$Pb dating) is calculated to be between 1925 (±5 years) and 1955 (±5 years) (table 1). Utilizing these dates and the aerial photographic evidence we conclude that the marsh started to develop between 1925 (±5 years) and 1937, resulting in a mean accretion rate between 1 and 1.2 mm yr$^{-1}$. In core S2 the base layer is found at a depth of 27 cm (Fig. 2, 3). $^{210}$Pb dating suggests that this layer was deposited in 1915 (±5 years). The aerial photograph of 1937 confirms the existence of the marsh at that time. Therefore, the mean accretion rate for core location S2 is estimated to be 2.8 mm yr$^{-1}$ (table 1). S3 has a marsh layer that is only 4.5 cm thick (Fig. 2, 3), but no $^{210}$Pb measurement is available for the base layer at that depth. Meanwhile the sample at 3.5 cm is calculated to be deposited in 1996, suggesting a mean accretion rate of 2.5 mm yr$^{-1}$. Aerial photographs indicate the beginning of the pioneer (*Spartina*-) marsh development between 1988 and 1995.

### *Accretion rates*

A reliable time series of accretion rates could only be drawn for the core S2, because the marsh layer in S3 is too thin to show significant variations, while $^{210}$Pb dating for S1 resulted in small accretion rates associated with large uncertainties. However, for S1, a general trend towards an increase of accretion rates can be observed from the beginning of the 1960s, resulting in a recent accretion rate between 3 and 3.5 mm yr$^{-1}$. Accretion rates for S2 indicate strong

variations over the last 75 years, ranging from about 1 mm $yr^{-1}$ up to 16 mm $yr^{-1}$ (Fig. 7). No clear trend can be observed, although accretion rates in the 1980's and 1990's seem to be higher. Two distinct peaks are found in 1982 and 1992 (according to $^{210}Pb$ dating).

## Hydrology and meteorology

Tide gauge data from1938 to 2007 were analyzed for historic trends (Fig. 8) and compared to $^{210}Pb$-derived marsh elevations (Fig. 9). It is shown that the MSL at the tide gauge *Hoernum Hafen* within that time period rose by about 2.1 mm $yr^{-1}$, slightly greater than the global rate of SLR of 1.8 mm $yr^{-1}$ during the same period (Church and White, 2011). The rise of MSL was accompanied by a mean increase of the MHW of about 4 mm $yr^{-1}$, while the MLW did not change significantly. The increase of both MHW and MSL was observed to accelerate since about the early 1980's. This corresponds to data analyzed by Wahl et al. (2010), who further pointed out that SLR rates during the last 10-15 years within the German Bight were higher than the global average, as reported by Church et al. (2008). The frequency of storm floods was analyzed based on their definition given by the German Maritime and Hydrographic Agency (BSH), where storm floods are water levels exceeding 1.5 m above MHW. Considering that the averaged yearly MHW from 1938 to 2007 is 0.9 m above NN, this corresponds to a storm level of 2.4 m NN. It was shown that storm frequency experienced a linear increase of 0.06 events $yr^{-1}$, while 1984 and 1990 were marked by the greatest number of storms with 10 and 11 events, respectively. During the same period the intensity of these storms did not significantly change.

As MHW increased rapidly within the last 50 years, salt marsh growth was not able to keep pace with this rise. An average of 2.6 and 1.3 mm $yr^{-1}$ was lost

417 relative to MHW at core location S1 and S2 respectively. Core location S3 was
418 observed to accrete at a rate of 2.5 mm $yr^{-1}$ since 1996. Meanwhile, during that
419 period, MHW strongly increased with a rate of 11 mm $yr^{-1}$ (Fig. 9). Marsh
420 elevation of S2 relative to MSL, on the other hand increased by 0.7 mm $yr^{-1}$, while
421 S1 decreased by 0.6 mm $yr^{-1}$ (Fig. 9).

422 **Influence of storm frequency and intensity on accretion rates**

423 The marsh at core location S2 floods when the water level reaches 134 cm (NN;
424 Fig. 2). Multiple linear regression analysis shows that storm intensity (ß=0.88,
425 $p<0.01$) describes accretion rates better than storm frequency (ß=0.06, $p>0.1$),
426 when considering all inundation events (Fig. 10). However, with an increasing
427 maximum storm level there is a decreasing influence of the storm intensity,
428 whereas the influence of storm frequency gradually increases. At a storm level of
429 260 cm, for example, storm frequency gives a ß of 0.86 ($p<0.01$), while storm
430 intensity cannot explain accretion rates significantly (ß=0.04, $p>0.1$; Fig. 11). It
431 appears that the storm level of 152 cm (equals an inundation height of 18 cm at
432 core location S2) is the turning point where the influence of storm frequency
433 becomes statistically significant ($p<0.1$); meanwhile the influence of storm
434 intensity progressively diminishes (Fig. 12).

435 # DISCUSSION

436 $^{210}$Pb geochronologies were used at three salt marsh levels (i) to determine the age
437 of the marsh and to reconstruct its evolution, (ii) to assess temporal variations of
438 accretion rates at all three core locations, and (iii) to identify the hydrological
439 parameters influencing marsh accretion.

## Support for accretion rate calculation

In contrast to the continuous deposition of $^{210}$Pb on the marsh surface, $^{137}$Cs serves as a marker horizon that can be used to calculate mean accretion rates in between the years 1963, 1986, and 2009, when the cores were extracted. It is, therefore, an additional independent geochronometer that allows for comparison with the $^{210}$Pb dating method, but not for derivation of higher resolved temporal accretion rates. Both the 1963 and 1986 peaks were found in cores S1 and S2. In core S1, $^{137}$Cs overestimates accretion rates compared to the $^{210}$Pb data and the aerial photograph of 1937 (Fig. 9). It seems that $^{137}$Cs has been transported further down in the soil column, although we are not certain of the mechanism. A very good agreement between the three methods ($^{137}$Cs, $^{210}$Pb, and aerial photographs) is found in core S2 and in core S3. $^{137}$Cs in core S2 shows two distinct peaks at depths of 5.5 cm and 17 cm. $^{210}$Pb dating is supported by these peaks; the layers at depths of 5.5 cm and 17 cm were estimated to be deposited in 1992 and 1961 respectively (Fig. 9). The absence of a peak in core S3 also supports what we can observe in the aerial photographs, as well as the $^{210}$Pb dating suggesting that the marsh development started after 1988.

Grain size data also support the $^{210}$Pb dating in core S2 to a certain degree. Two layers (5.5 cm and 9.5 cm) show an elevated fraction of coarse-grained sediments in comparison to the other layers (Fig. 3). $^{210}$Pb dating calculates that these layers were deposited in 1992 (±5 years) and 1985 (±5 years). In 1990, the highest number of storms occurred during the last 70 years (Fig. 8), 2 of which were among the 5 most severe storm surges (measured at *Hörnum Hafen*) in recorded history. Meanwhile, the year 1984 was marked by the second most frequent storm events during the last 70 years (Fig. 8). We expect that the higher energy of

storms allows for the transport of coarser-grained materials onto the marsh by both waves and currents.

## Mean accretion rates

The spatial pattern of mean accretion rates shows a decrease from the low marsh towards the inner marsh (table 1). This is a typical spatial phenomenon observed on many marshes by various authors (Bartholdy et al., 2004; Cahoon and Reed, 1995; French and Spencer, 1993; Pethick, 1981; Temmerman et al., 2003a). Meanwhile the mean accretion rate for the pioneer marsh zone is lower than the one in the low marsh zone. Resuspension of sediment during the early stage of the marsh development could be the reason for this pattern. The measured accretion rates generally compare well with mean accretion rates measured on the peninsula of Skallingen, where Bartholdy et al. (2004) found the accretion rate on the Skallingen marsh to vary between 2 mm $yr^{-1}$ on the inner marsh and 4 mm $yr^{-1}$ on the outer marsh. Measurements of Kirchner and Ehlers (1998) in the eastern part of Sylt, however, have shown much higher accretion rates between 5.8 mm $yr^{-1}$ and 15.2 mm $yr^{-1}$, but grain sizes in this section of Sylt are much finer, indicating different hydrodynamic conditions favoring settling of sediment.

## Temporal variations of accretion rates

S2 shows strong temporal variations of accretion with a period of higher rates found during the 1980s and 1990s including two distinct peaks in 1982 and 1992 and a rapid decrease in accretion rates during the last 20 years. This pattern strongly resembles the periods of high storm activity (Fig. 10, 11). Although temporal variations of accretion rates in S1 should only be considered as an approximation, a trend towards increasing accretion rates to current values

between 3-3.5 mm $yr^{-1}$ is observed. The few data points that exist for S3 show a constant accretion rate of 2.5 mm $yr^{-1}$.

Accretion rates at core location S2 during calm periods seem to lie close to the rates of eustatic SLR (Fig. 10, 11), while, during stormy years, accretion rates are much higher than SLR. This behavior shows the importance of storms for the resilience of salt marshes towards eustatic SLR. Even though, accretion rates during calm years are still sufficiently high, a considerable decrease in storminess would lower the marsh elevation and possibly affect the marsh zonation.

## Historic development of the marsh

Using the data presented in the previous section it is possible to reconstruct the historic evolution of the marsh: Marsh development at our study site seems to have started after about 1915. Prior to marsh development, we assume a bare sandy beach slope at that location. The age of the base layer at core location S2 indicates that marsh development started during a period of rapidly increasing MHW and MLW levels (Jensen and Mudersbach, 2004; Wahl et al., 2010). Increasing inundation frequencies may have triggered the development of pioneer marsh vegetation, such as *Salicornia* and *Suaeda*, probably sheltered by a seaward sandy ridge. At some point, the sandy ridge at the seaward edge moved offshore and a cliff arose due to increased hydrodynamics caused by more frequent inundation events. As a consequence, a channel developed in front of the marsh, which probably acted as a tidal channel, building up levees at the landward and seaward side (Pedersen and Bartholdy, 2007). According to the aerial photograph in 1988, the pioneer marsh started to develop on top of the sand bar and slowly spread towards the cliff at the marsh edge, stabilizing the latter. Decreased hydrodynamics in the vicinity of the sand bar, a constantly low MLW-level, and a

spread of the invasive species *Spartina anglica* after 1987 (Loebl et al., 2006), may have triggered that process. Today the cliff is located far inside the marsh and the pioneer marsh seems to expand further onto the tidal flat and accrete faster than MSLR.

The inner part of the marsh accreted with the slowest overall accretion rate. While the base layer is approximately 30 cm above the base layer in the central part of the marsh, marsh development started between 1925 and 1937. During the first few decades of growth, aerial photographs indicate that considerable amounts of sand may have been blown onto this part of the marsh; although, accretion rates were too low to detect significant temporal variations. The topography of the marsh platform has been flattened during the last 75 years due to higher accretion rates in the middle of the marsh, than on the landward side of the marsh.

## Influence of storms on accretion

The analysis presented in this study focuses on the historical vertical development of a single salt marsh. It is shown that an increase of storminess positively correlates with marsh accretion rates. While many authors have focused on the destructive, erosional influence of storms on salt marshes (e.g. Callaghan et al. 2010, Mariotti and Fagherazzi 2010, van de Koppel et al. 2005), our methods are not able to reproduce the lateral marsh development and their implications on accretion processes, but rather the vertical marsh accretion.

Vertical accretion (at core location S2) was shown to be closely linked to past storm patterns with accretion rates of up to 16 mm $yr^{-1}$ in very stormy years. Linear regression analysis showed that both storm intensity and storm frequency are important factors influencing accretion rates. Storm frequency does not seem to be the driving factor of accretion if storm levels do not rise higher than 18 cm

above the marsh surface at S2. The importance of frequency greatly increases above this threshold level (Fig. 12). We hypothesize that the presence and the height of the vegetation could be the reason for this threshold.

Assuming that the threshold value we found for the core S2 is true for different marsh elevations as well, we can identify two different driving factors for marsh accretion in the lower and the higher parts of the marsh: In the lower marsh zones, where inundation is frequent and usually higher than the vegetation height, accretion rates increase with increasing inundation frequency. Inundation frequency at low elevations, in turn, is highly correlated with the MHW level and possibly caused by SLR. In the higher parts of the marsh, where inundation is less frequent and heights of the inundation are often lower or just slightly higher than the vegetation height, we expect the mean strength of the storms to be more important than the actual number of storms.

These findings are especially relevant when considering possible implications on storm related accretion processes. Assuming that more sediment is in suspension when storm water levels are high, the solution of the mass balance equation for incoming and settling sediment (Mudd et al., 2010; Temmerman et al., 2003a) results in an exponential increase of accretion rates with higher storm water levels (Fig. 13; Temmerman et al., 2003a). Considering our results, the effect of storm intensity on salt marsh accretion is suggested to be stronger at low storm water levels than at high storm water levels, resulting in a logarithmic rather than an exponential relationship between storm water levels and accretion rates (Fig. 13). The height at which the logarithmic curve starts to flatten is hypothesized to be connected to the height of the vegetation. Vegetation has a strong effect on flow velocities and the Reynolds number within the vegetation canopy and can therefore influence the flocculation and break-up processes of the sediment in

suspension (Winterwerp, 2002). Low flow velocities within the vegetation canopy could therefore result in larger floc sizes and corresponding settling velocities, while high flow velocities could decrease the floc sizes and decrease the settling velocities of the sediment particles (Bartholomä et al., 2009). This would infer that the depth-averaged settling velocity would decrease with inundation heights that exceed the vegetation height and result in a flatting of the above mentioned curve. We must emphasize that this hypothesis should be further investigated by explicitly examining flocculation processes over salt marsh surfaces during storm events.

# Conclusions

In accordance with the available literature, $^{210}$Pb has proven to be a good tool for determination of sediment accretion rates on salt marshes. $^{137}$Cs data and aerial photographs independently supported the $^{210}$Pb dating and the derived accretion rates. However, restrictions and limitation of the method can be recognized in core S1 and S3. Based on the results of this study we make the following conclusions:

(1) While not always coincident with one another, both storm frequency and intensity seem to affect salt marsh accretion rates. In very stormy years, accretion rates can increase 5-fold above mean value. Frequent and strong storms have shown that they can lead to accretion rates which are higher than MSLR and, therefore are considered as an important factor for the ability of marshes to keep pace with eustatic SLR.

(2) We show that eustatic SLR slightly increases accretion rates during calm wind periods, while a surplus of accretion is observed in stormy years, leading to a net increase of marsh elevation relative to mean sea level,

accompanied by a slight decrease in elevation relative to the more rapidly rising mean tidal high water level.

(3) There exists a threshold for inundation depth (18 cm) on the investigated marsh at which the relative importance of storm frequency and intensity reverses. Storm intensity seems to be the driving factor for high accretion rates below an inundation depth of 18 cm, while storm frequency is more important above this inundation depth. The influence of vegetation is suggested to be the reason for this threshold.

(4) The existence of a threshold for inundation depth implies that accretion of higher marsh zones is crucially dependent on the storm intensity, while lower marsh parts rather depend on the development of storm frequency and mean high water level, possibly influenced by a mean sea level rise. The different major driving factors for the marsh zones may lead to changes in marsh zonation, if storm activity and SLR rate change in the future.

Further investigation, including short-term measurements of accretion rates during storm events and modeling is necessary to better understand the singular effects of storm intensity, storm frequency, and sea level rise on accretion processes. Also, more marshes in mesotidal environments need to be investigated to test whether a similar critical inundation depth threshold exists elsewhere and the hypothesis of vegetation being responsible can be verified.

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# References

Ahrendt, K.and R. Köster. 1998. Sylt - einst und jetzt. In Umweltatlas Wattenmeers, Band 1, Nordfriesisches und Dithmarscher Wattenmeer, eds. Nationalpark Schleswig-Holsteinisches Wattenmeer (Tönning) and Umweltbundesamt (Berlin), 38-39. Stuttgart: Eugen Ulmer.

Ahrendt, K.and J. Thiede. 2001. Naturräumliche Entwicklung Sylts - Vergangenheit und Zukunft. In Sylt - Klimafolgen für Mensch und Küste, eds. Daschkeit A. and P. Schottes, 69-112. Berlin: Springer.

Allen, J. R. L. 2000. Morphodynamics of Holocene salt marshes: a review sketch from the Atlantic and Southern North Sea coasts of Europe. Quaternary Science Reviews 19:1155-1231.

ALW - Amt für Land- und Wasserwirtschaft Husum. 1997. Fachplan Küstenschutz Sylt - Fortschreibung. Husum.

Andersen, T. J., O. A. Mikkelsen, A. L. Møller, and P. Morten. 2000. Deposition and mixing depths on some European intertidal mudflats based on 210Pb and 137Cs activities. Continental Shelf Research 20:1569-1591.

Appleby, P. G.and F. Oldfield. 1978. The calculation of lead-210 dates assuming a constant rate of supply of unsupported 210Pb to the sediment. Catena 5:1-8.

Appleby, P. G.and F. Oldfield. 1983. The assessment of 210Pb data from sites with varying sediment accumulation rates. Hydrobiologia 103:29-35.

Armentano, T. V.and G. M. Woodwell. 1975. Sedimentation Rates in a Long Island Marsh Determined by 210 Pb Dating. American Society of Limnology and Oceanography 20:452-456.

642 Bartholdy, J., C. Christiansen, and H. Kunzendorf. 2004. Long term variations in backbarrier salt
643 marsh deposition on the Skallingen peninsula - the Danish Wadden Sea. Marine Geology 203:1-
644 21.
645 Bartholdy, J., J. B. T. Pedersen, and A. T. Bartholdy. 2010. Autocompaction of shallow silty salt
646 marsh clay. Sedimentary Geology 223:310-319.
647 Bartholomä, A., A. Kubicki, T. Badewien, and B. Flemming. 2009. Suspended sediment transport
648 in the German Wadden Sea—seasonal variations and extreme events. Ocean Dynamics 59:213-
649 225.
650 Bellucci, L. G., M. Frignani, J. K. Cochran, S. Albertazzi, L. Zaggia, G. Cecconi, and H. Hopkins.
651 2007. Pb-210 and Cs-137 as chronometers for salt marsh accretion in the Venice Lagoon - Links to
652 flooding frequency and climate change. Journal of Environmental Radioactivity 97:85-102.
653 Beniston, M., D. Stephenson, O. Christensen, C. Ferro, C. Frei, S. Goyette, K. Halsnaes, T. Holt,
654 K. Jylhä, B. Koffi, J. Palutikof, R. Schöll, T. Semmler, and K. Woth. 2007. Future extreme events
655 in European climate: an exploration of regional climate model projections. Climatic Change 81:71-
656 95.
657 BSH - Bundesamt für Seeschifffahrt und Hydrographie. 2008. Gezeitentafeln 2009 - Europäische
658 Gewässer. Hamburg and Rostock: BSH.
659 Cahoon, D. R. and D. J. Reed. 1995. Relationships among Marsh Surface Topography,
660 Hydroperiod, and Soil Accretion in a Deteriorating Louisiana Salt Marsh. Journal of Coastal
661 Research 11:357-369.
662 Callaghan, D. P., T. J. Bouma, P. Klaassen, D. Van der Wal, M. J. F. Stive, and P. M. J. Herman.
663 2010. Hydrodynamic forcing on salt-marsh development: Distinguishing the relative importance
664 of waves and tidal flows. Estuarine, Coastal and Shelf Science 89:73-88.
665 Chmura, G. L., A. Coffey, and R. Crago. 2001. Variation in surface sediment deposition on salt
666 marshes in the Bay of Fundy. Journal of Coastal Research 17:221-227.
667 Church, J. and N. White. 2011. Sea-Level Rise from the Late 19th to the Early 21st Century.
668 Surveys in Geophysics:1-18.
669 Church, J., N. White, T. Aarup, W. Wilson, P. Woodworth, C. Domingues, J. Hunter, and K.
670 Lambeck. 2008. Understanding global sea levels: past, present and future. Sustainability Science
671 3:9-22.

672 Compton, A. H. 1923. A Quantum Theory of the Scattering of X-rays by Light Elements. Physical
673 Review 21:483-502.
674 De Groot, A. 2009. Salt-marsh sediment: Natural γ-radioactivity and spatial patternsthesis,
675 University of Groningen.
676 Delaune, R. D., W. H. Patrick, and R. J. Buresh. 1978. Sedimentation rates determined by 137Cs
677 dating in a rapidly accreting salt marsh. Nature 275:532-533.
678 Dijkema, K. S. 1987. Geography of Salt Marshes in Europe. Zeitschrift Fur Geomorphologie
679 31:489-499.
680 Fischer-Bruns, I., H. Storch, J. González-Rouco, and E. Zorita. 2005. Modelling the variability of
681 midlatitude storm activity on decadal to century time scales. Climate Dynamics 25:461-476.
682 French, J. 2006. Tidal marsh sedimentation and resilience to environmental change: Exploratory
683 modelling of tidal, sea-level and sediment supply forcing in predominantly allochthonous systems.
684 Marine Geology 235:119-136.
685 French, J. R. 1993. Numerical simulation of vertical marsh growth and adjustment to accelerated
686 sea-level rise, North Norfolk, U.K. Earth Surface Processes and Landforms 18:63-81.
687 French, J. R. and T. Spencer. 1993. Dynamics of sedimentation in a tide-dominated backbarrier
688 salt marsh, Norfolk, UK. Marine Geology 110:315-331.
689 Goodbred, S. L.and S. A. Kuehl. 1998. Floodplain processes in the Bengal Basin and the storage
690 of Ganges-Brahmaputra river sediment: an accretion study using 137Cs and 210Pb geochronology.
691 Sedimentary Geology 121:239-258.
692 Harrison, E. Z.and A. L. Bloom. 1977. Sedimentation rates on tidal salt marshes in Connecticut.
693 JOURNAL OF SEDIMENTARY RESEARCH 47:1484-1490.
694 He, Q. and D. E. Walling. 1996a. Interpreting particle size effects in the adsorption of 137Cs and
695 unsupported 210Pb by mineral soils and sediments. Journal of Environmental Radioactivity
696 30:117-137.
697 He, Q. and D. E. Walling. 1996b. Use of fallout Pb-210 measurements to investigate longer-term
698 rates and pattern of overbank sediment deposition on the floodplains of lowland rivers. Earth
699 Surface Processes and Landforms 21:141-154.
700 Hildebrandt, V., J. Gemperlein, U. Zeltner, and W. Peteresen. 1993. Landesweite Biotopkartierung
701 - Kreis Nordfriesland: Landschaftsentwicklung - Aktuelle Situation - Flächenschutz. Kiel:
702 Landesamt für Naturschutz und Landschaftspflege Schleswig-Holstein.

703 Jensen, J.and C. Mudersbach. 2004. Zeitliche Änderungen in den Wasserstandszeitreihen an den
704 Deutschen Küsten. In Klimaänderung und Küstenschutz, Conference Proceedings, eds. Gönnert
705 G., H. Grassl, D. Kelletat, H. Kunz, B. Probst, H. von Storch, and J. Sündermann, 115-128.
706 Hamburg.
707 Kelletat, D. 1992. Coastal Erosion and Protection Measures at the German North Sea Coast.
708 Journal of Coastal Research 8:699-711.
709 Kirchner, G. and H. Ehlers. 1998. Sediment Geochronology in Changing Coastal Environments:
710 Potentials and Limitations of the 137Cs and 210Pb Methods. Journal of Coastal Research 14:483-
711 492.
712 Kirwan, M. and S. Temmerman. 2009. Coastal marsh response to historical and future sea-level
713 acceleration. Quaternary Science Reviews 28:1801-1808.
714 Kirwan, M. L.and G. R. Guntenspergen. 2010. Influence of tidal range on the stability of coastal
715 marshland. Geophysical Research Letters 115:F02009.
716 Kirwan, M. L., G. R. Guntenspergen, A. D'Alpaos, J. T. Morris, S. M. Mudd, and S. Temmerman.
717 2010. Limits on the adaptability of coastal marshes to rising sea level. Geophysical Research
718 Letters 37:L23401.
719 Koide, M., A. Soutar, and E. D. Goldberg. 1972. Marine geochronology with210Pb. Earth and
720 Planetary Science Letters 14:442-446.
721 Kolker, A. S., S. L. Goodbred Jr, S. Hameed, and J. K. Cochran. 2009. High-resolution records of
722 the response of coastal wetland systems to long-term and short-term sea-level variability.
723 Estuarine, Coastal and Shelf Science 84:493-508.
724 Kunzendorf, H., K.-C. Emeis, and C. Christiansen. 1998. Sedmentation in the Central Baltic Sea
725 as Viewed by Non-Destructive Pb-210-dating Geografisk Tidsskrift 98:1-8.
726 Loebl, M., J. Beusekom, and K. Reise. 2006. Is spread of the neophyte Spartina anglica recently
727 enhanced by increasing temperatures? Aquatic Ecology 40:315-324.
728 Malvern Instruments Ldt. 2010. Mastersizer 2000.
729 http://www.malvern.de/LabGer/products/Mastersizer/MS2000/mastersizer2000.htm. Accessed 31
730 August 2010.
731 Mariotti, G. And S. Fagherazzi. 2010. A numerical model for the coupled long-term evolution of
732 salt marshes and tidal flats. Journal Geophysical Research 115:F01004.

Milne, G. A., A. J. Long, and S. E. Bassett. 2005. Modelling Holocene relative sea-level observations from the Caribbean and South America. Quaternary Science Reviews 24:1183-1202.

Möller, I. 2006. Quantifying saltmarsh vegetation and its effect on wave height dissipation: Results from a UK East coast saltmarsh. Estuarine, Coastal and Shelf Science 69:337-351.

Mudd, S. M., A. D'Alpaos, and J. T. Morris. 2010. How does vegetation affect sedimentation on tidal marshes? Investigating particle capture and hydrodynamic controls on biologically mediated sedimentation. Journal of Geophysical Research 115:F03029.

Nikulina, A. 2008. The imprint of anthropogenic activity versus natural variability in the fjords of Kiel Bight: Evidence from Sediments. PhD thesis, University of Kiel.

Orson, R., W. Panageotou, and S. P. Leatherman. 1985. Response of Tidal Salt Marshes of the U.S. Atlantic and Gulf Coasts to Rising Sea Levels. Journal of Coastal Research 1:29-37.

Pedersen, J. B. T.and J. Bartholdy. 2007. Exposed salt marsh morphodynamics: An example from the Danish Wadden Sea. Geomorphology 90:115-125.

Pedersen, J. B. T., J. Bartholdy, and C. Christiansen. 2007. 137Cs in the Danish Wadden Sea: contrast between tidal flats and salt marshes. Journal of Environmental Radioactivity 97:42-56.

Pethick, J. S. 1981. Long-term accretion rates on tidal salt marshes. Journal of Sedimentary Research 51:571-577.

Redfield, A. C. 1972. Development of a New England Salt Marsh. Ecological Monographs 42:201-237.

Reed, D. J. 1995. The response of coastal marshes to sea-level rise: Survival or submergence? Earth Surface Processes and Landforms 20:39-48.

Reise, K., M. Baptist, B. P., N. Dankers, L. Fischer, B. Flemming, A. P. Oost, and C. Smit. 2010. The Wadden Sea - A Universally Outstanding Tidal Wetland. Wadden Sea Ecosystem 29. Common Wadden Sea Secretariat, Wilhelmshaven, Germany: 7-24.

Rockel, B. and K. Woth. 2007. Extremes of near-surface wind speed over Europe and their future changes as estimated from an ensemble of RCM simulations. Climatic Change 81:267-280.

Temmerman, S., G. Govers, P. Meire, and S. Wartel. 2003a. Modelling long-term tidal marsh growth under changing tidal conditions and suspended sediment concentrations, Scheldt estuary, Belgium. Marine Geology 193:151-169.

762 Temmerman, S., G. Govers, S. Wartel, and P. Meire. 2003b. Spatial and temporal factors
763 controlling short-term sedimentation in a salt and freshwater tidal marsh, Scheldt estuary,
764 Belgium, SW Netherlands. Earth Surface Processes and Landforms 28:739-755.
765 The Trilateral Monitoring and Assessment Program - TMAP. 2006. Ubgkal07: Topographie DK
766 und SH. Nationalpark Schleswig-Holsteinisches Wattenmeer. http://www.waddensea-
767 secretariat.org/TMAP/Data-Unit/Data.html. Accessed 20 November 2008
768 van de Koppel, J., D. van der Wal, J. P. Bakker, and P. M. J. Herman. 2005. Self-organization and
769 vegetation collapse in salt marsh ecosystems. American Naturalist 165:E1-E12.
770 von Storch, H.and R. Weisse. 2008. Regional storm climate and related marine hazards in the
771 Northeast Atlantic. In Climate Extremes and Society, eds. Diaz H. F. and R. J. Murnane, 54-73.
772 Cambridge: Cambridge University Press.
773 Wahl, T., J. Jensen, and T. Frank. 2010. On analysing sea level rise in the German Bight since
774 1844. Natural Hazards and Earth System Sciences 10:171-179.
775 Walling, D. E., A. L. Collins, and H. M. Sichingabula. 2003. Using unsupported lead-210
776 measurements to investigate soil erosion and sediment delivery in a small Zambian catchment.
777 Geomorphology 52:193-213.
778 Williams, H. 2003. Modeling Shallow Autocompaction in Coastal Marshes Using Cesium-137
779 Fallout: Preliminary Results from the Trinity River Estuary, Texas. Journal of Coastal Research
780 19:180-188.
781 Winterwerp, J. C. 2002. On the flocculation and settling velocity of estuarine mud. Continental
782 Shelf Research 22:1339-1360.
783 Woth, K., R. Weisse, and H. von Storch. 2006. Climate change and North Sea storm surge
784 extremes: an ensemble study of storm surge extremes expected in a changed climate projected by
785 four different regional climate models. Ocean Dynamics 56:3-15.
786 WSA - Wasser- und Schifffahrtsamt Tönning. 2007. Wasserstandsinformationen: Hörnum/Sylt.
787 http://www.wsv.de/wsa-toe/service/wasserstandinfo/index.html. Accessed 27 August 2010.
788

# TABLES

Table 1: Ages of base layers and mean sedimentation rates: Comparison of $^{210}$Pb datings with information from aerial photographs.

| Core name | Depth of base layer | Age of base layer ($^{210}$Pb) | Age of base layer (aerial photographs) | Sedimentation rate (mm/year) |
|---|---|---|---|---|
| **S1** | 8.5cm | 1925-1955 | <1937 | 1-1.2 |
| **S2** | 27 | 1915 | <1937 | 2.8 |
| **S3** | 4.5cm | No measurement | 1988-1995 | 2.5 (since 1996) |

# FIGURE LEGENDS

**Fig. 1:** The study area is located in the southeastern North Sea (cell 1), in the southern part of the island of Sylt (cell 2). The cores were taken on a transect in three dominant vegetation zones, indicated by points (cell 3).

**Fig. 2:** Topographic profile and marsh zonation of the investigated salt marsh. Core locations and the sandy base layer are indicated by triangles and a dashed line respectively.

**Fig. 3:** Grain size composition (%) and bulk density calculations (kg m$^{-3}$), as described in equation 5, for all 3 cores and all depths (cm) that were measured. Grain size composition is depicted in the bar graph and bulk density by the line graph. The depth of the sandy base layer is indicated by the dashes line.

**Fig 4:** Aerial photographs of the investigated salt marsh from 1937 (a), 1958 (b), 1988 (c), and 1995 (d). Dark colours indicate vegetated areas. Bright colours indicate sand. Source: Landesbetrieb für Küstenschutz, Nationalpark und Meeresschutz Schleswig-Holstein (LKN-SH)

**Fig. 5:** Excess $^{210}$Pb (Bq kg$^{-1}$) in all three cores and all depths (cm) that were measured. Horizontal error bars indicate propagated errors for excess $^{210}$Pb. Measurements without horizontal error bars were measured below detection limit. Vertical error bars represent the thickness of the measured layer.

**Fig. 6:** $^{137}Cs$ (Bq $kg^{-1}$) in all three cores and all depths (cm) that were measured. Horizontal error bars indicate measurement errors of $^{137}Cs$. Vertical error bars represent the thickness of the measured layer.

**Fig. 7:** Marsh sedimentation rates from 1938-2003 (mm $yr^{-1}$). Horizontal error bars represent the averaged uncertainty of the $^{210}Pb$ dating.

**Fig. 8:** Hydrological data from 1938-2007 at tide gauge Hörnum Hafen (Sylt). Storm intensity (stars), mean tidal high water (MHW), mean sea level (MSL), and mean tidal low water (MLW) are given in meter above 'Normal Null' (NN). A 19-years running mean is given for MHW, MSL, and MLW. Storm frequency (bars) is the number of storm events that exceeded the level of 2.4 m above NN. Source: Wahl 2010, Hartwig 2010.

**Fig. 9:** Historic marsh elevations for all three cores derived from $^{210}Pb$ and $^{137}Cs$ data. Due to several data points below the detection limit in core S1, two graphs are displayed, comparing the fastest possible accretion rates (open circles) with the slowest possible accretion rates (filled circles). For validation of the data, the $^{137}Cs$ peaks are included (open diamonds). The error bars (as shown in figure 6) were omitted for clarity. The mean high water and the mean sea level (MHW and MSL: solid lines) are displayed as 5-years running averages.

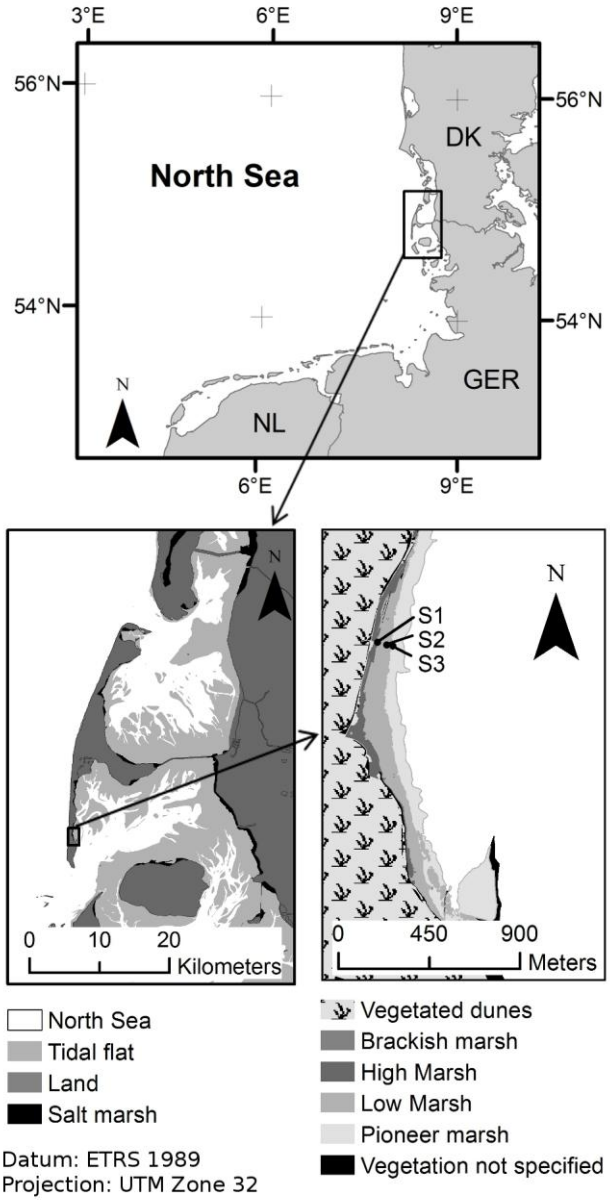
**Fig. 10:** Comparison of sedimentation rates (stars) at core location S2 with storm intensity (open circles), defined as the mean height for all high water levels exceeding 1.34 m (NN).

**Fig. 11:** Comparison of sedimentation rates (stars) at core location S2 with storm frequency (open circles), defined as the number of water levels, exceeding 2.4 m (NN).

**Fig. 12:** Results of linear regression analysis: ß- and p-values (circles and triangles respectively) for different storm water levels (m above NN) are shown. ß- and p-values refer to results of multiple linear regression analyses of storm frequency (filled symbols) and storm intensity (open symbols) with sedimentation rates at core location S2.

**Fig. 13:** Conceptual scheme of how vegetation is influencing accretion rates at various storm water levels. The "No vegetation scenario" does not reflect the resuspension happening in absence of a vegetation canopy.

836 # FIGURES

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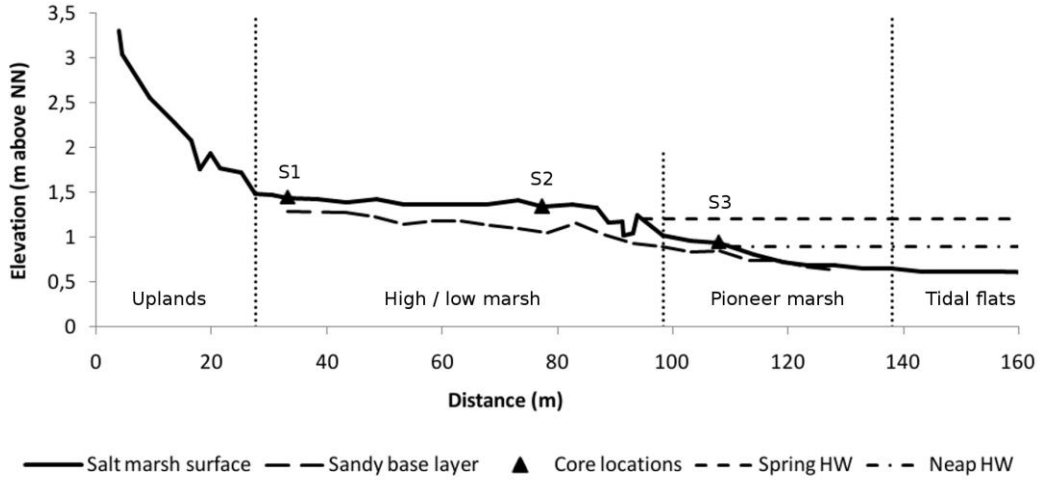


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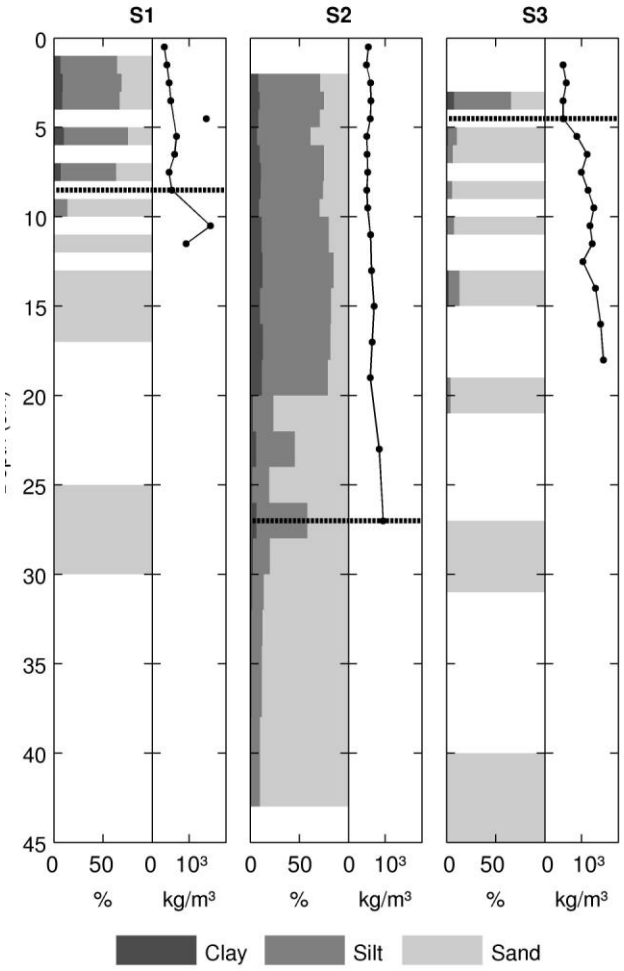


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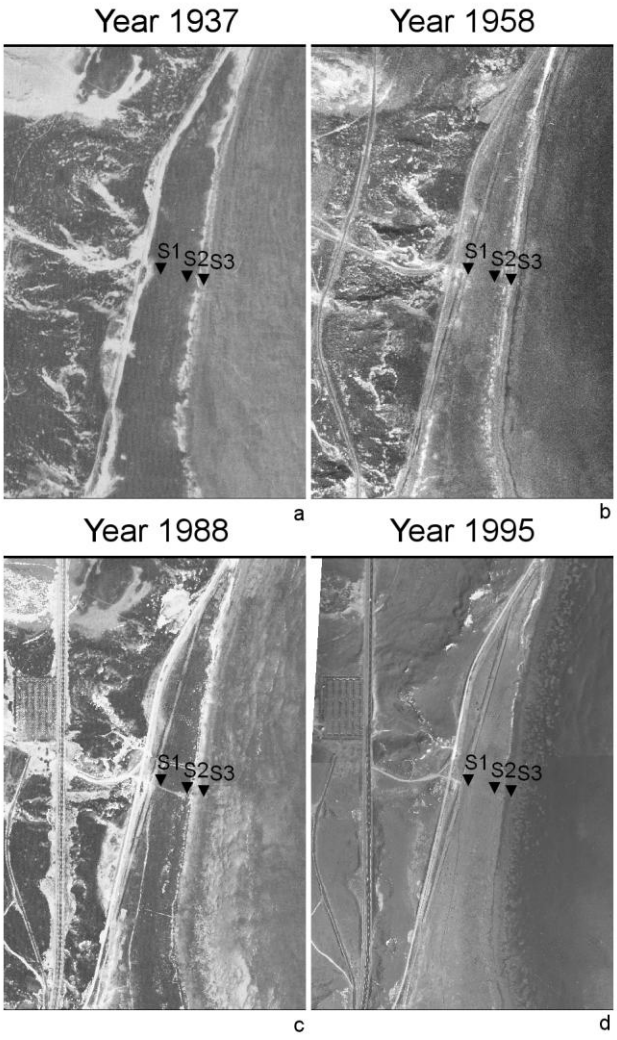
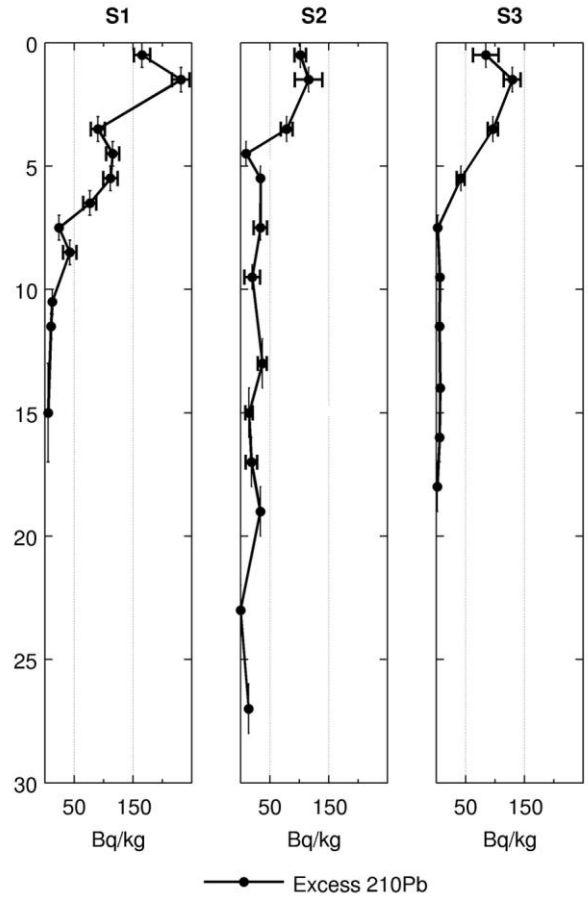
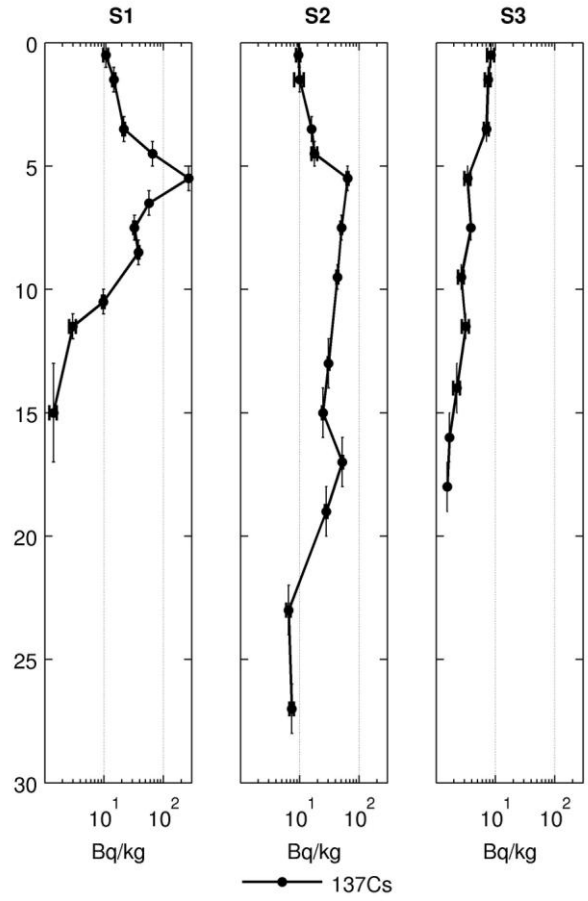

Year 1937
Year 1958
S1 S2 S3
S1 S2 S3
a
b
Year 1988
Year 1995
S1 S2 S3
S1 S2 S3
c
d

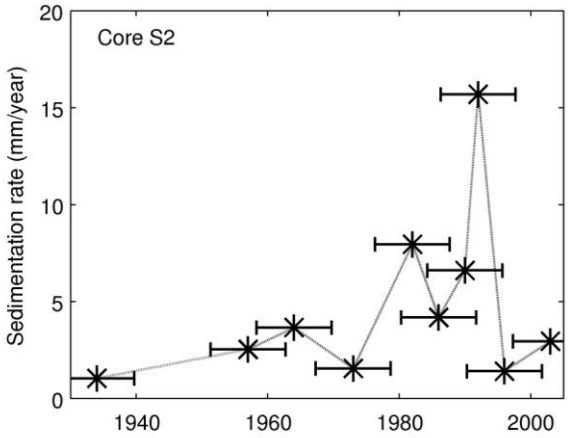
840


S1
S2
S3
0
5
10
15
20
25
30
50
150
Bq/kg
Excess 210Pb

841


S1
S2
S3
0
5
10
15
20
25
30
$10^1$
$10^2$
Bq/kg
137Cs

842

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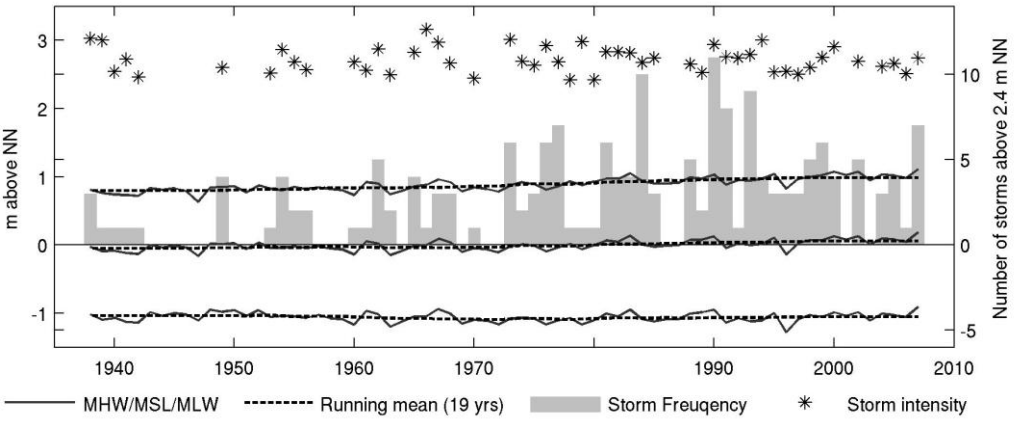


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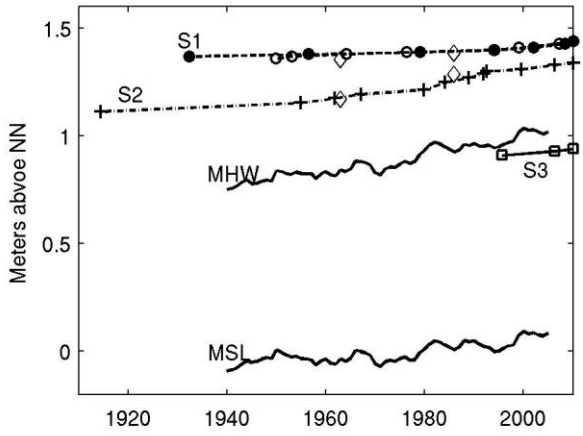


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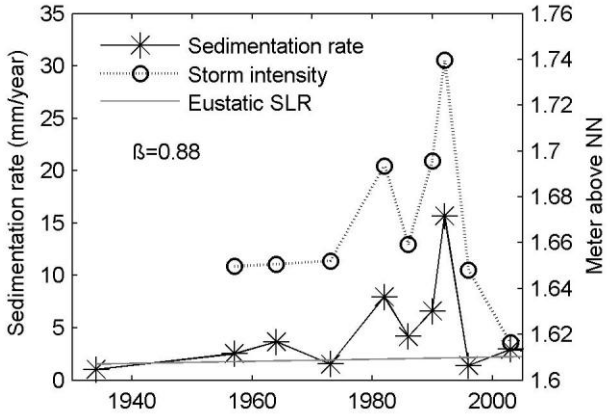


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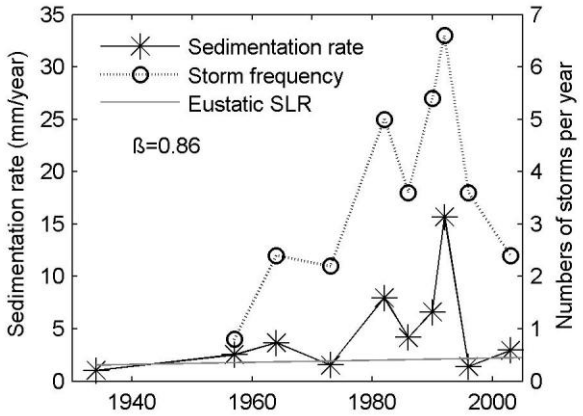
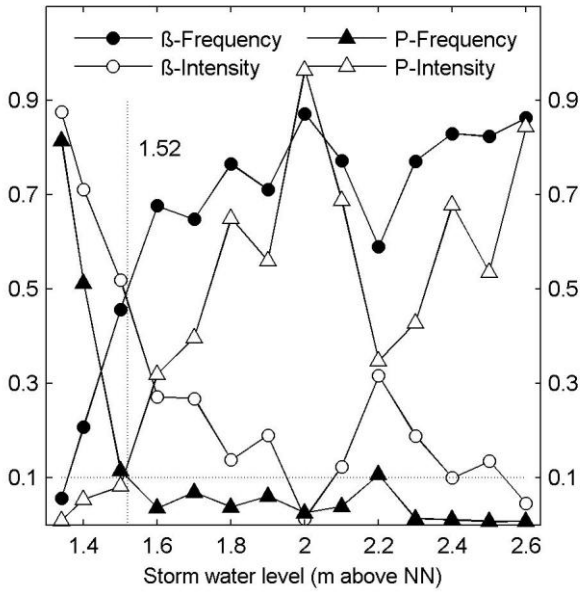
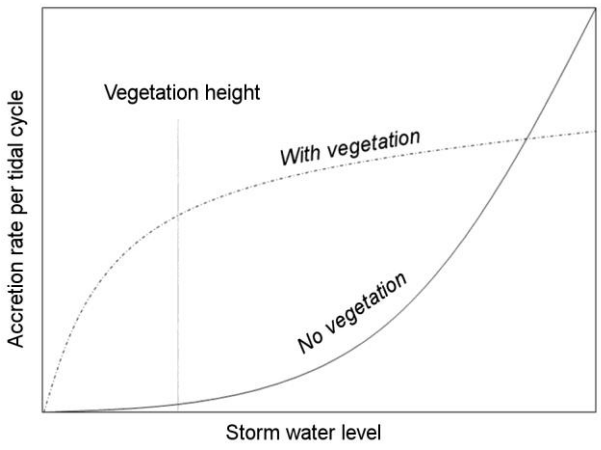

Sedimentation rate
Storm frequency
Eustatic SLR
ß=0.86
Sedimentation rate (mm/year)
Numbers of storms per year
0
5
10
15
20
25
30
35
0
1
2
3
4
5
6
7
1940
1960
1980
2000

847

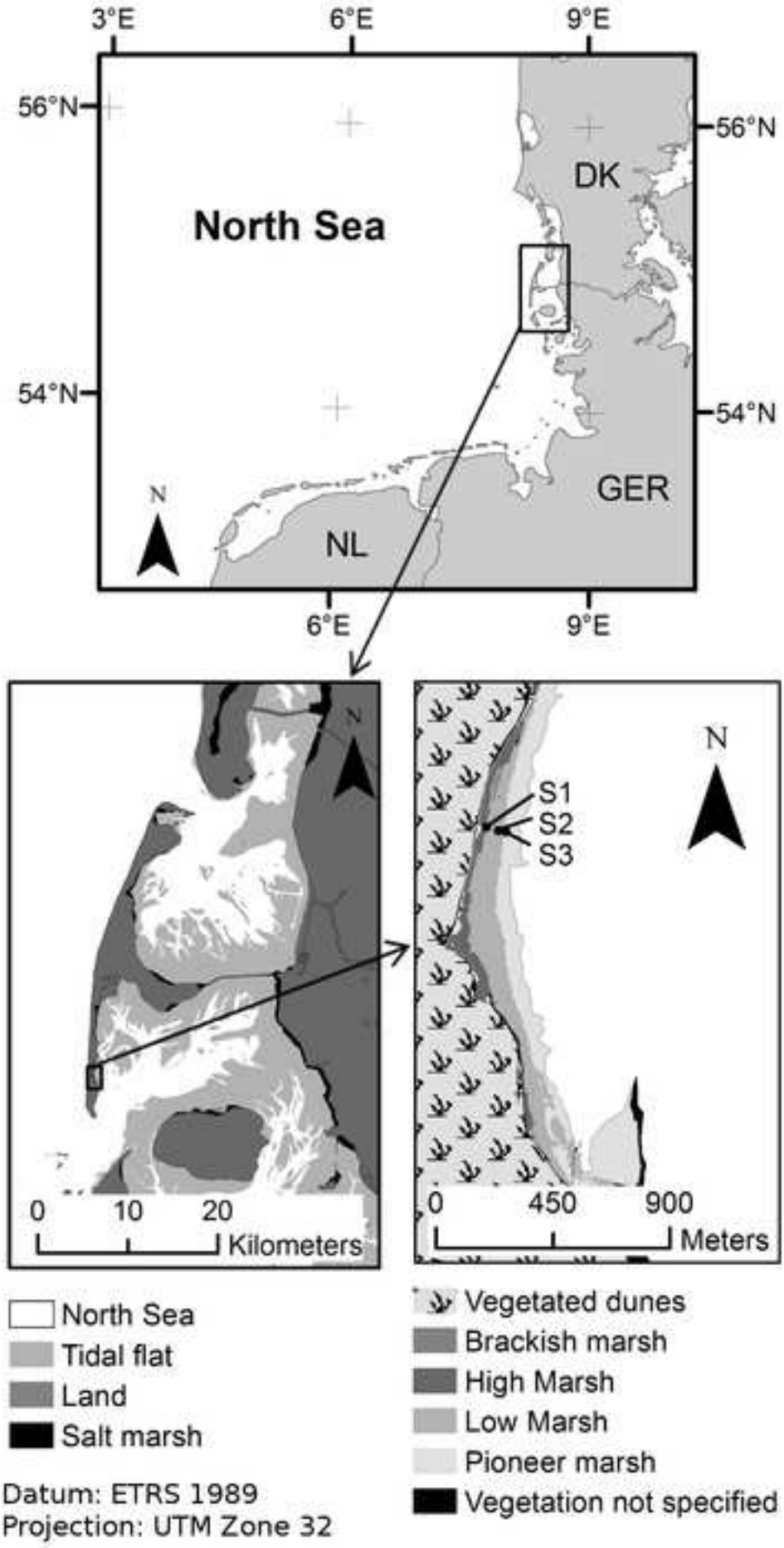

ß-Frequency
P-Frequency
ß-Intensity
P-Intensity
1.52
0.1
0.3
0.5
0.7
0.9
1.4
1.6
1.8
2
2.2
2.4
2.6
Storm water level (m above NN)

848


Vegetation height
With vegetation
No vegetation
Accretion rate per tidal cycle
Storm water level

849

Figure 1
Click here to download high resolution image



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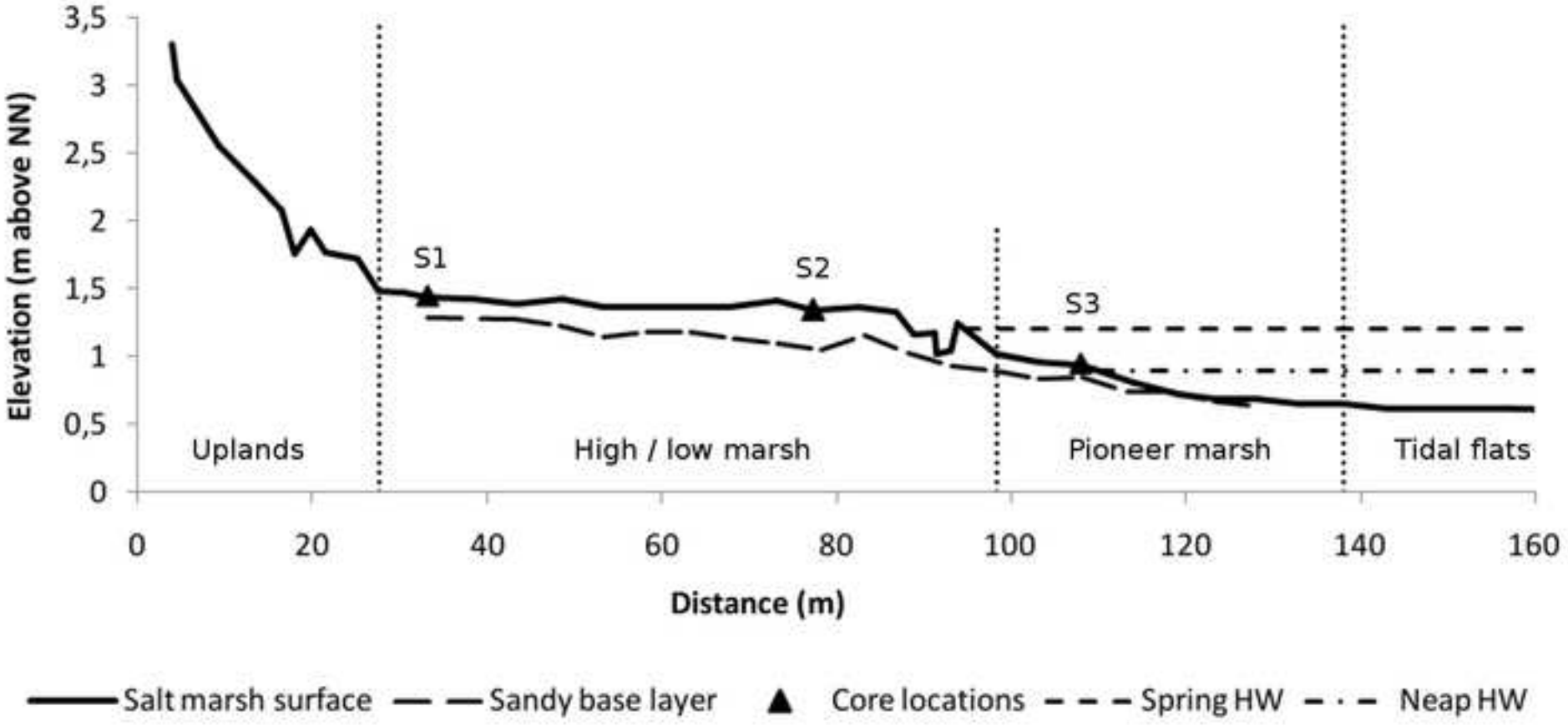

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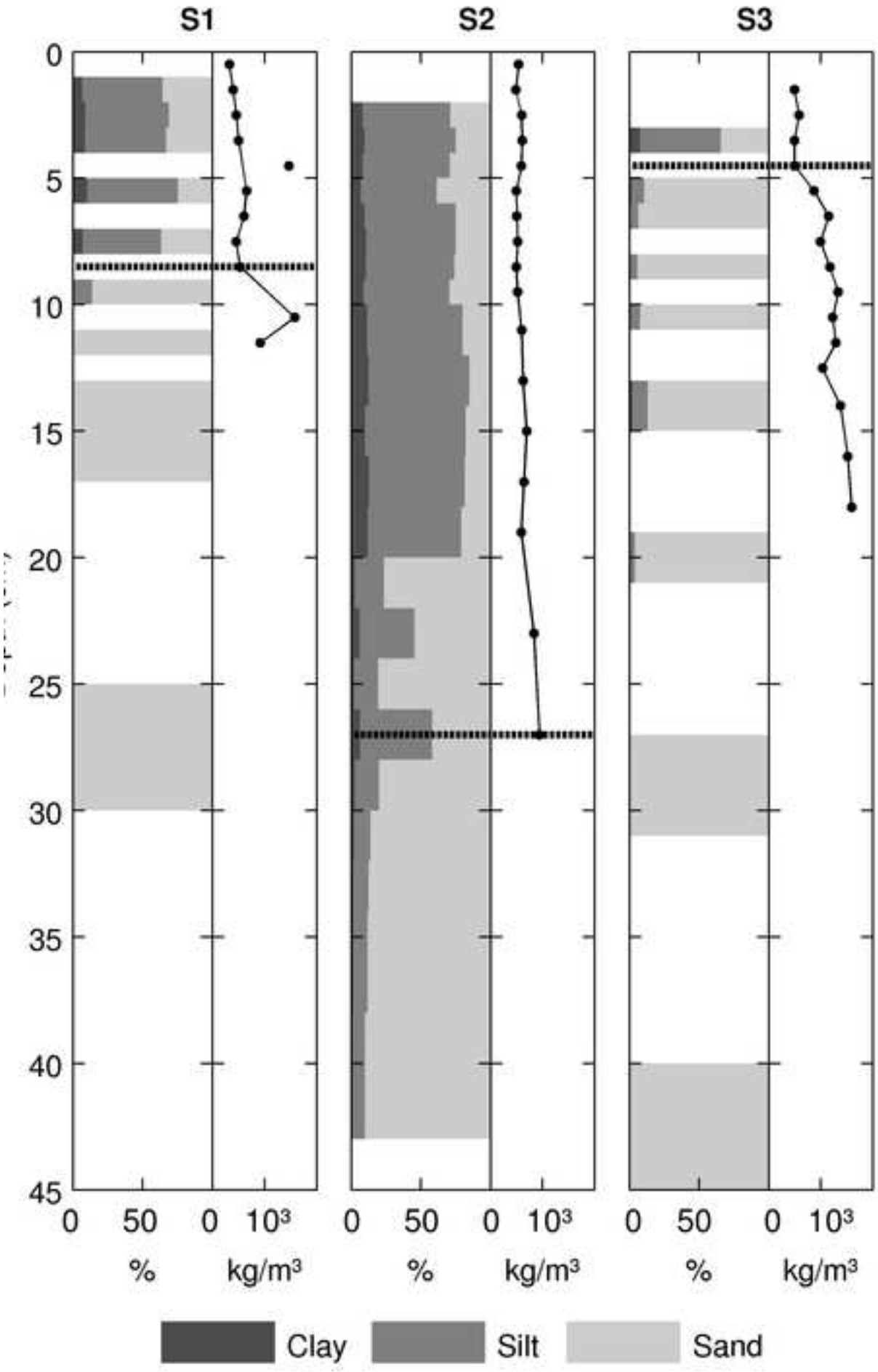

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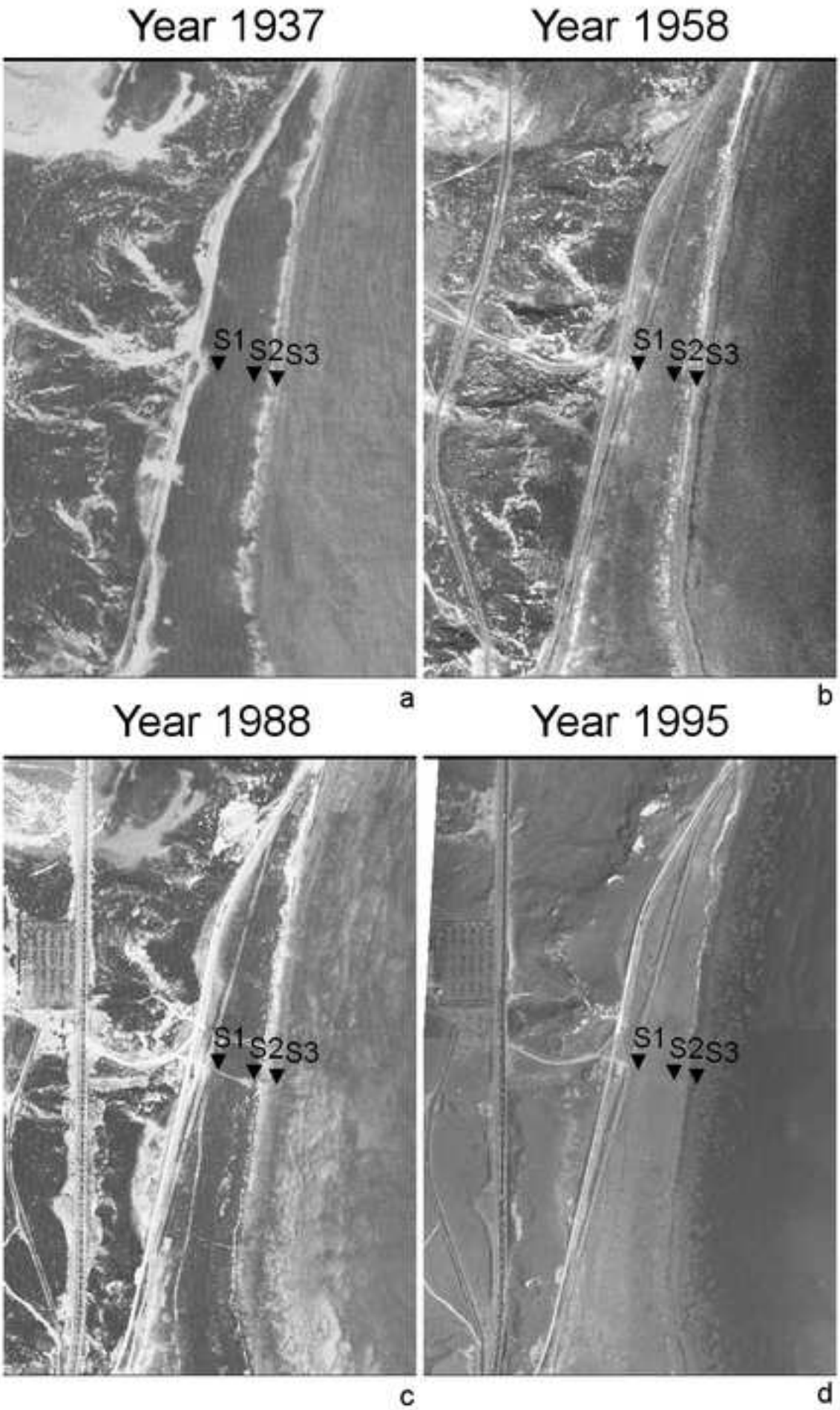

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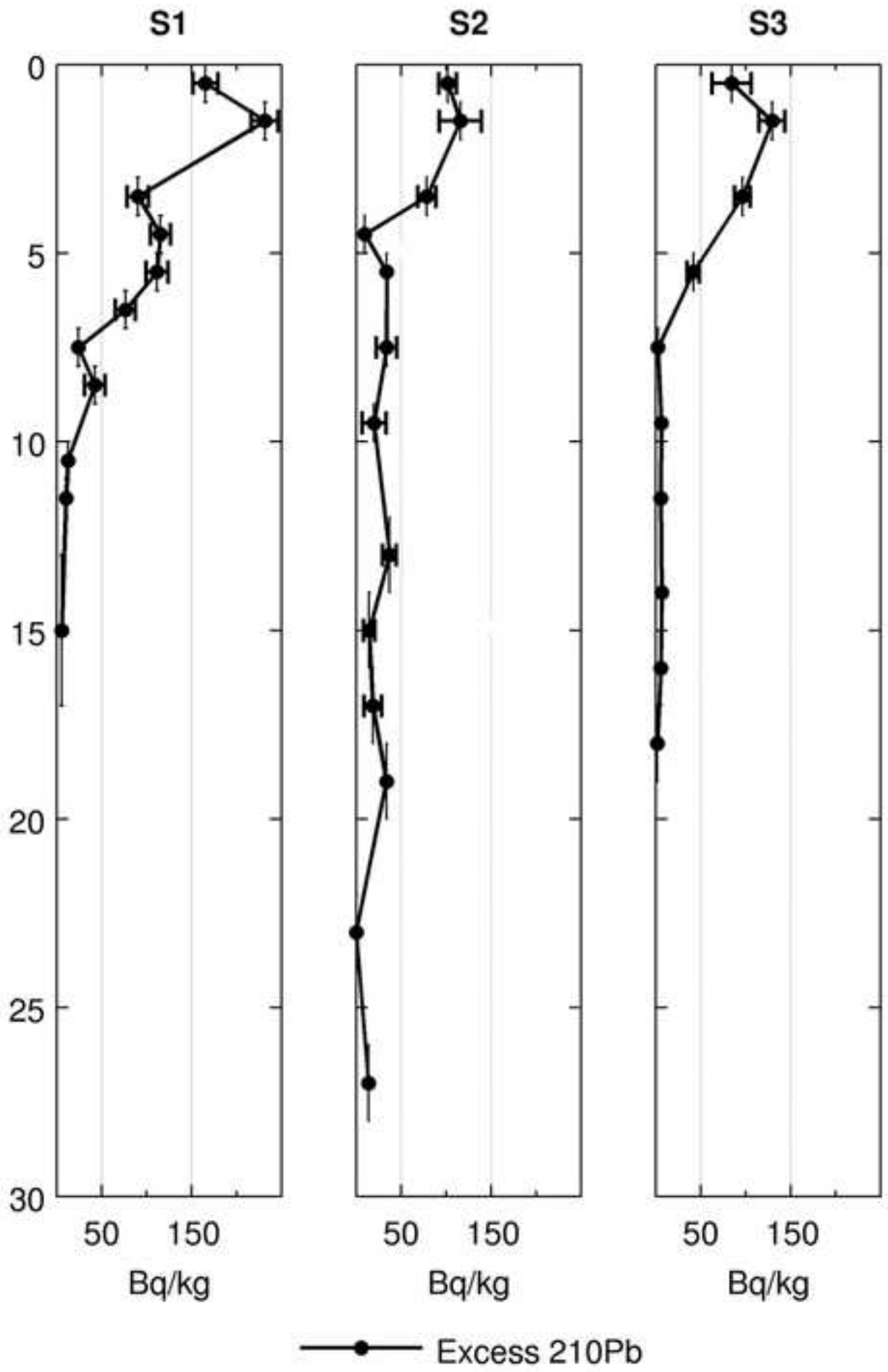

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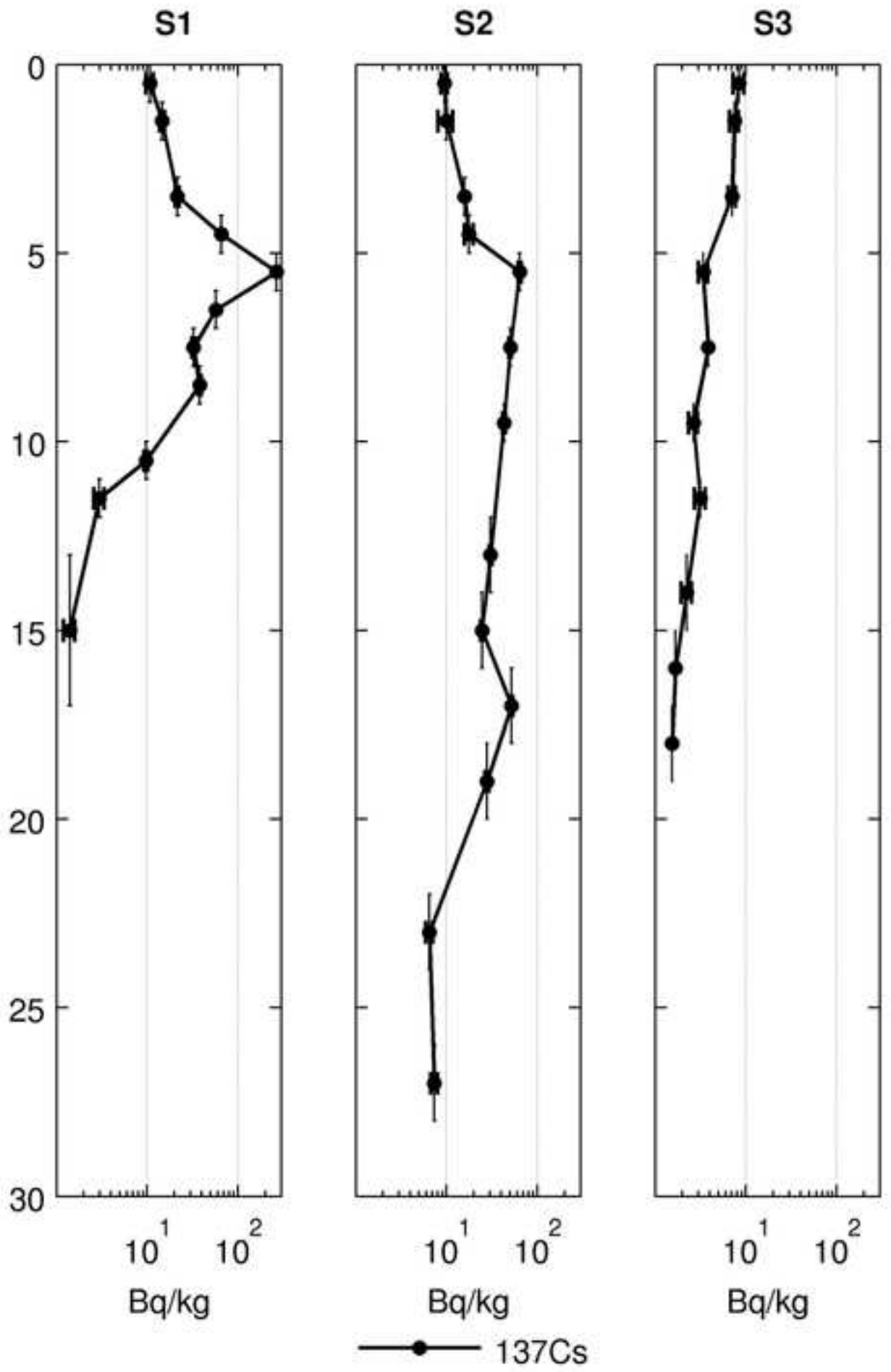

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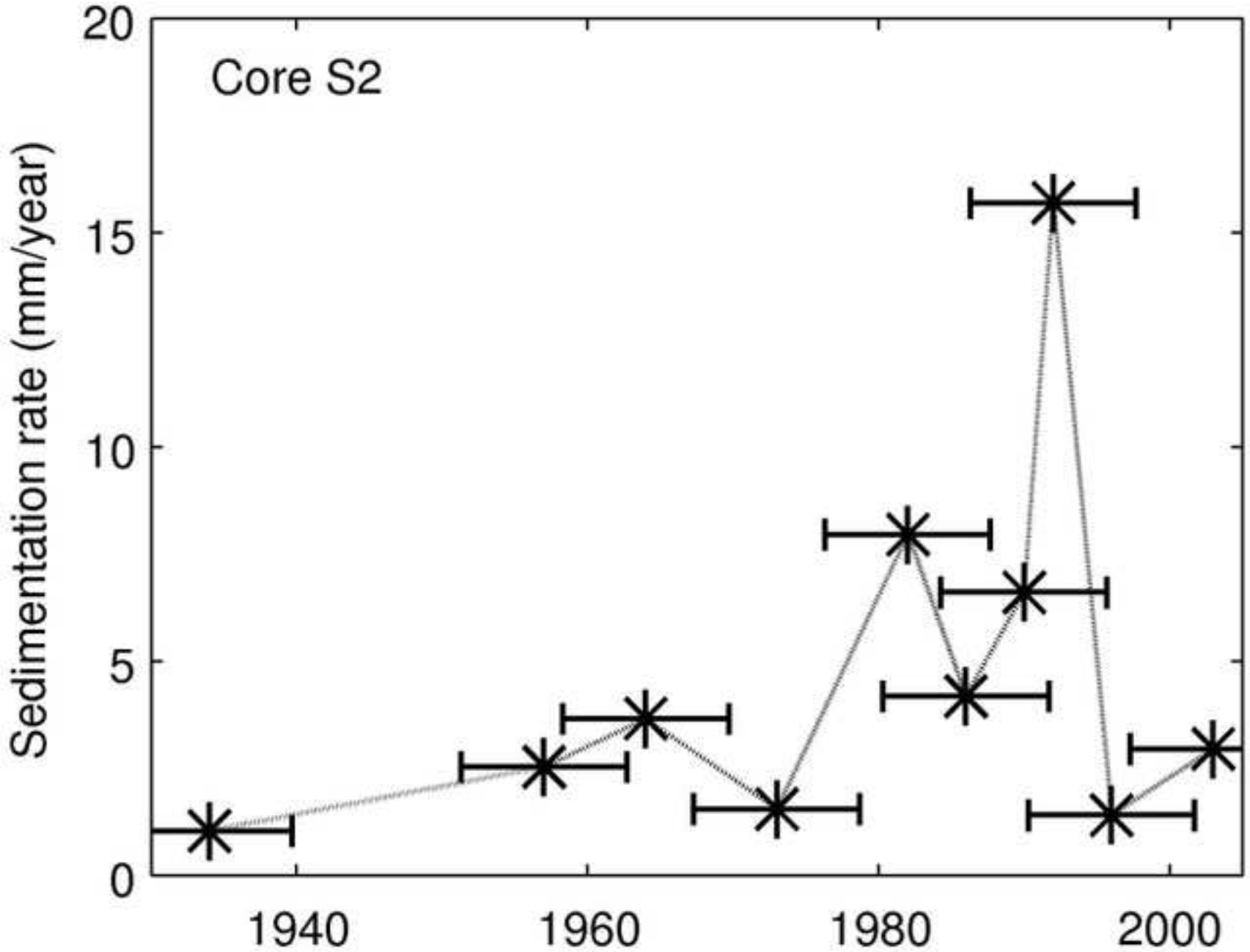

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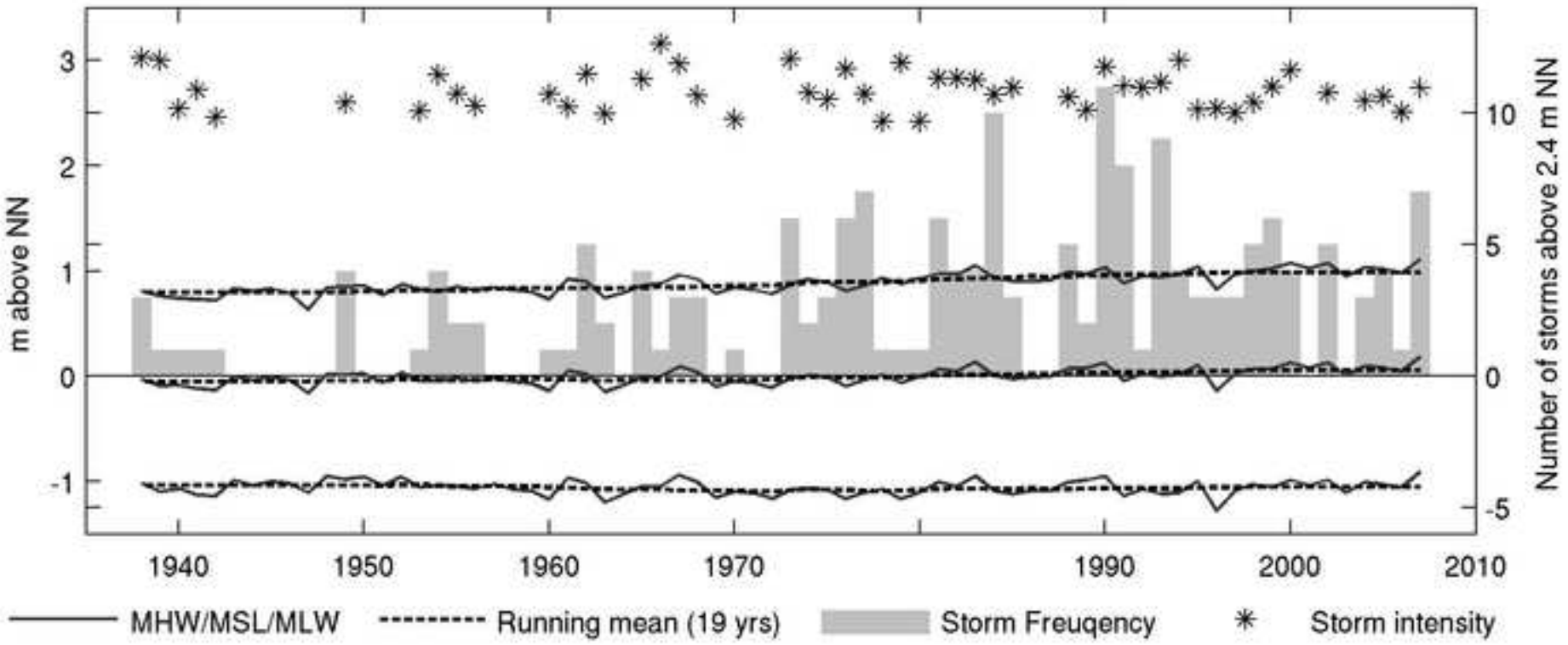

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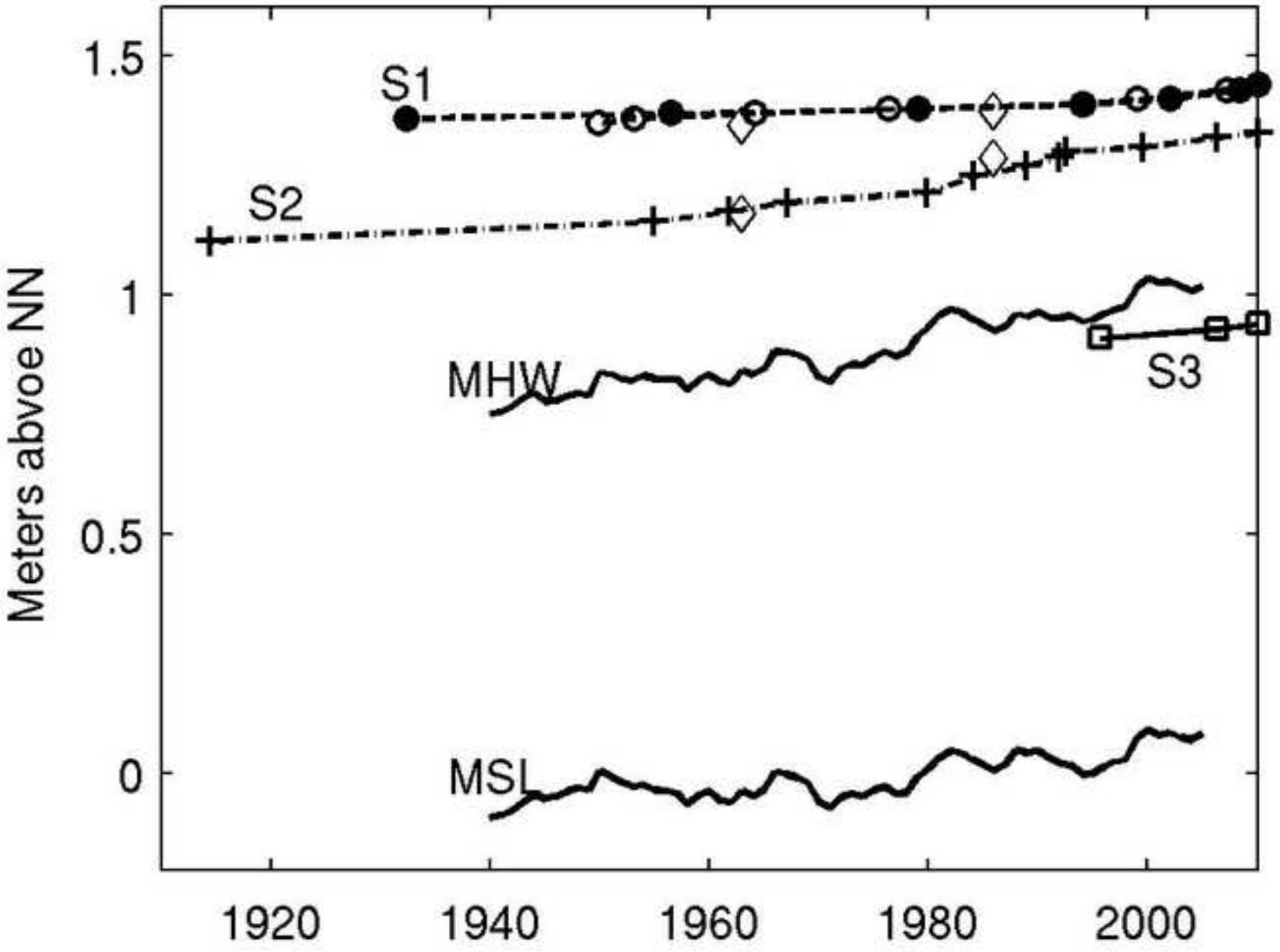

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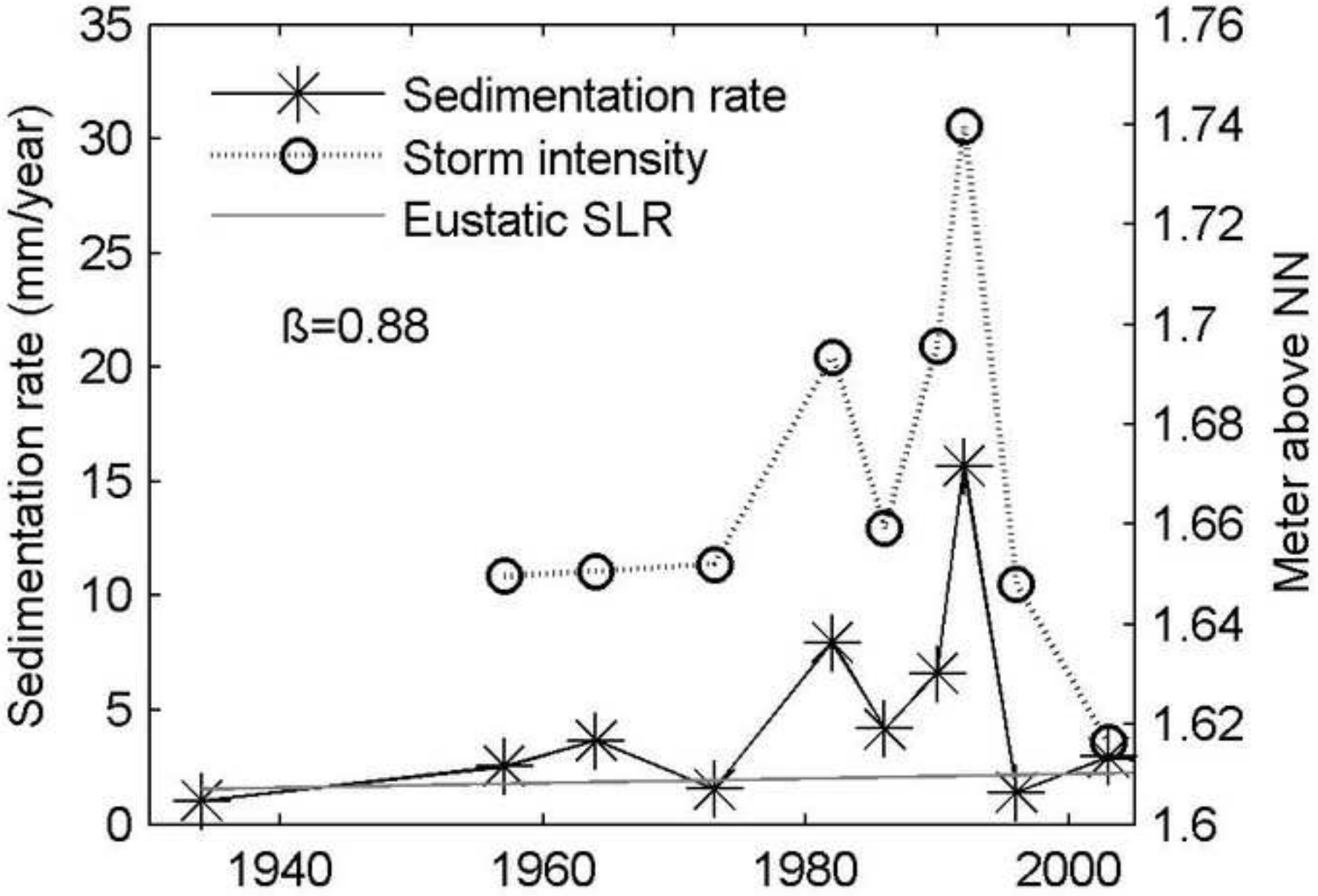

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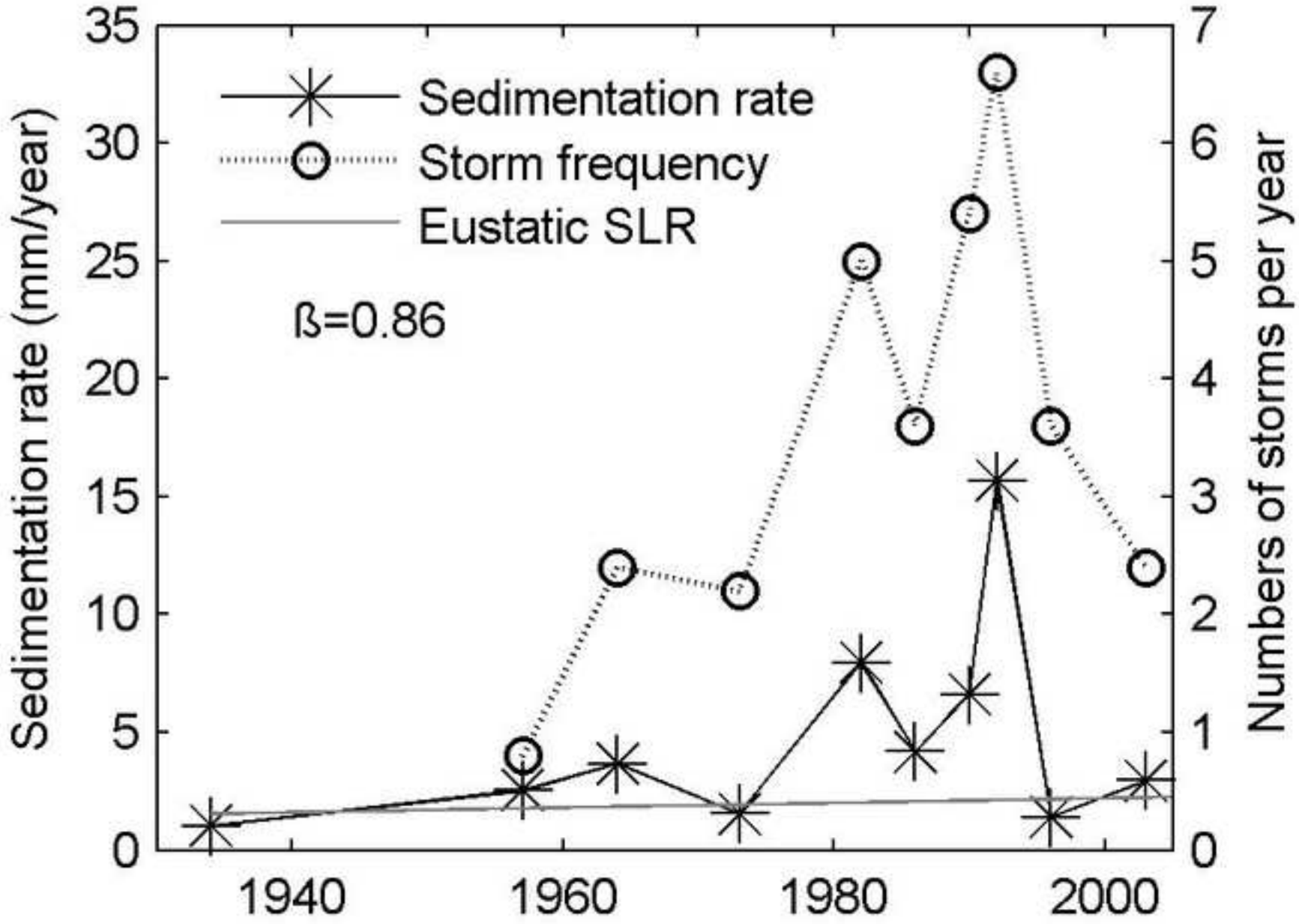

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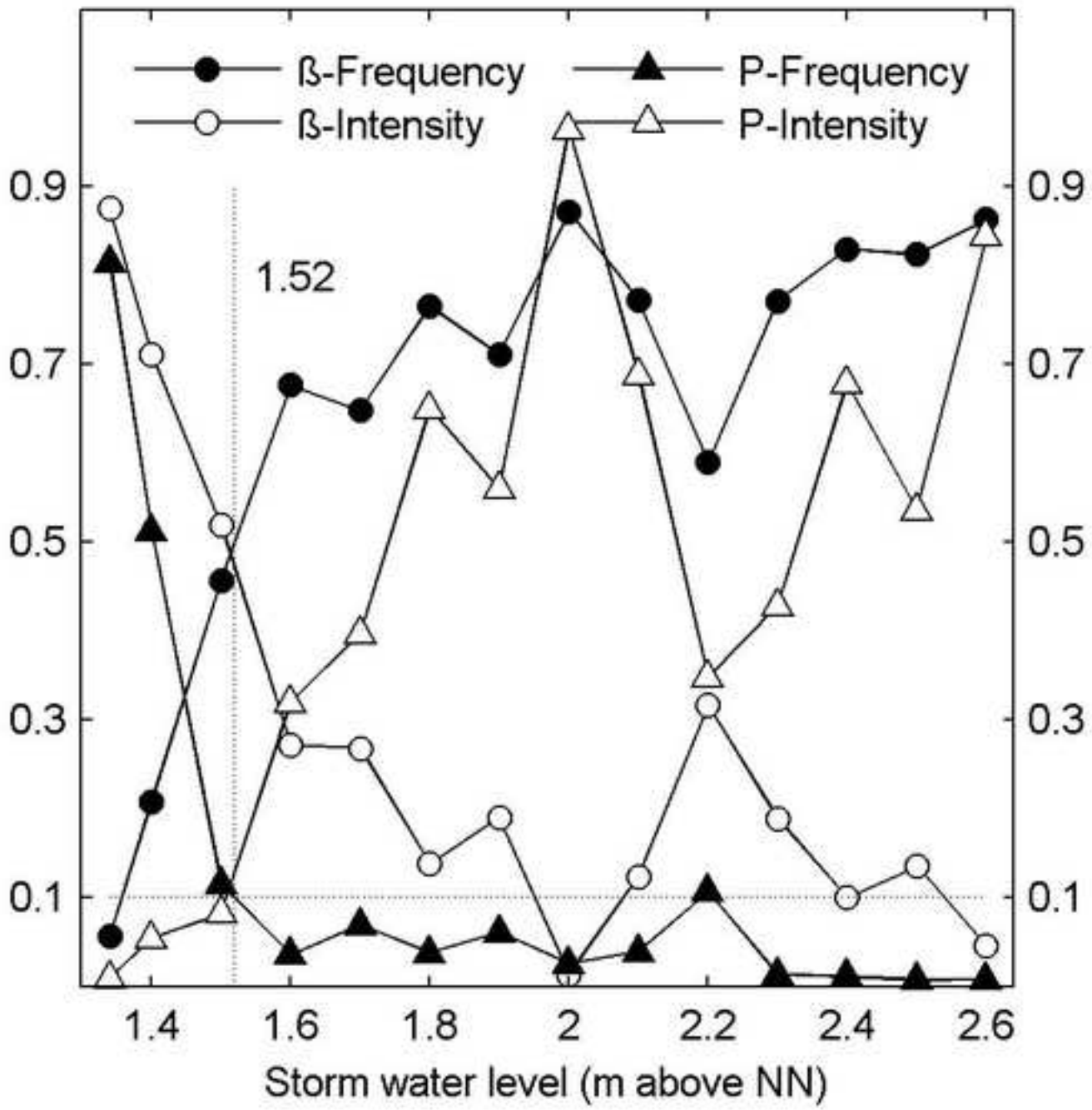

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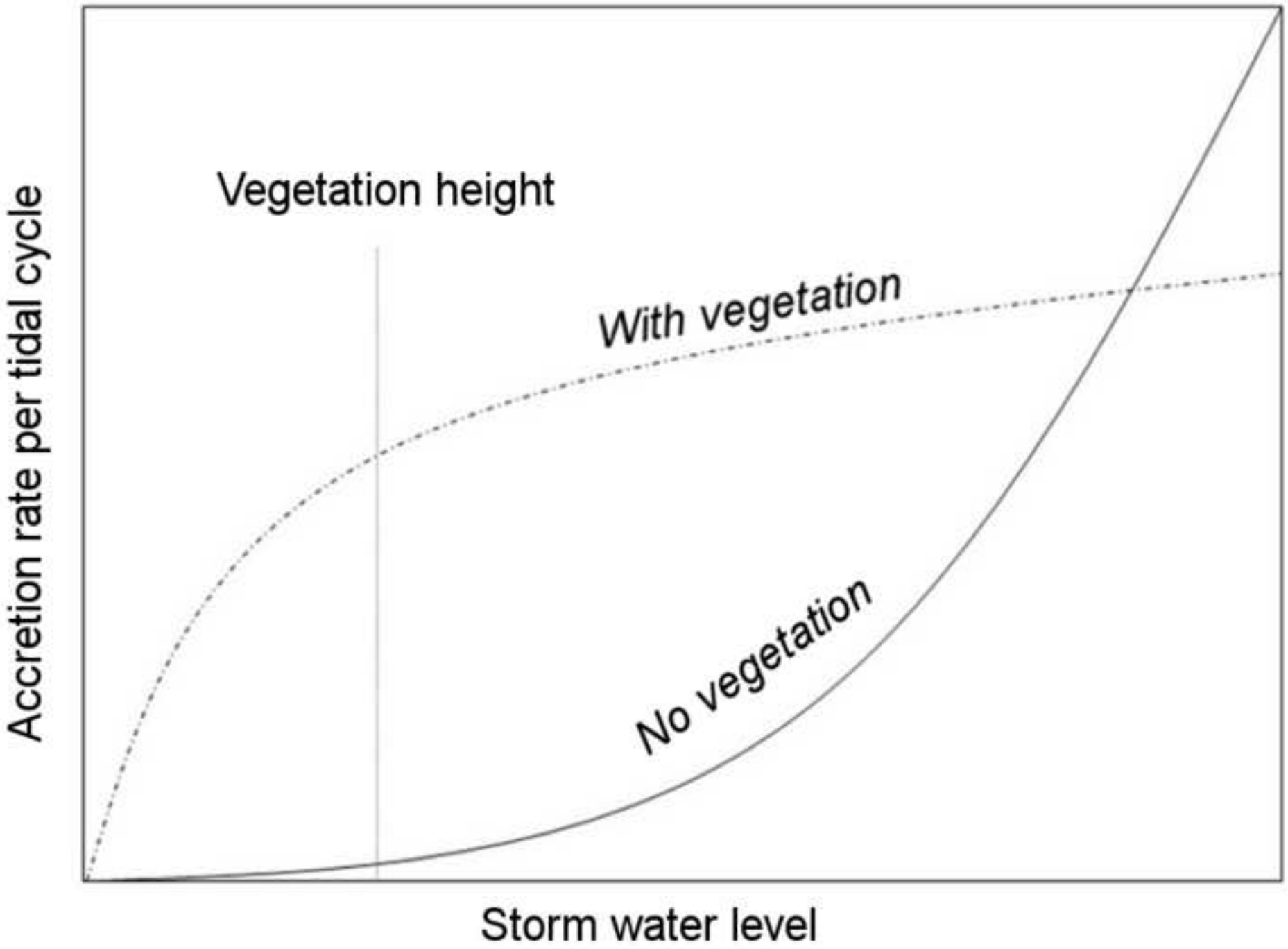

Table 1: Ages of base layers and mean sedimentation rates: Comparison of $^{210}$Pb datings with information from aerial photographs.

| Core name | Depth of base layer | Age of base layer ($^{210}$Pb) | Age of base layer (aerial photographs) | Sedimentation rate (mm/year) |
|---|---|---|---|---|
| **S1** | 8.5cm | 1925-1955 | <1937 | 1-1.2 |
| **S2** | >27 | 1915 | <1937 | 2.8 |
| **S3** | 4.5cm | 1978-1988 | 1988-1995 | 2.5 (since 1996) |